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INTERNAL REPORT

THERMAL CONDUCTIVITY VALUES AND PRANDTL NUMBERS OF NITROGEN FROM 133° TO 740° K FOR PRESSURES BETWEEN 1 AND 240 ATMOSPHERES

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Robert E. Wood

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BRANCH BRANCH OF RESEARCH AND LABORATORY SERVICES

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APPLIED RESEARCH

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CONTENTS

ILLUSTRATIONS

TABLES

THERMAL CONDUCTIVITY VALUES AND PRANDTL NUMBERS OF NITROGEN FROM 133° TO 740° K FOR PRESSURES BETWEEN 1 AND 240 ATMOSPHERES

by

Robert E. Wood,[1/] F. W. Baer,[2/] and W. J. Boone, Jr.[3/]

ABSTRACT

The temperature dependency of the low-density thermal conductivity coefficients, λ°_T, of nitrogen, 100° to 1,200° K, is correlated with the Keyes' equation, $\lambda^\circ_T = aT^{1/2} / \left(1 + bT^{-1}\, 10^{-12/T}\right)$.

The residual thermal conductivity, $\lambda_{T,P} - \lambda^\circ_T$, (the difference between the thermal conductivity of the compressed and dilute gas at a given temperature) was found to be a function of the thermal pressure coefficient, $\left(\frac{\partial P}{\partial T}\right)_V$, and two parameters, α and β.

The equation $\lambda_{T,P} = \lambda^\circ_T + \alpha \left[\left(\frac{\partial P}{\partial T}\right)_V\right]^\beta$ represented 509 experimental higher pressure thermal conductivity values in the temperature range 131.2° to 973.15° K for pressures to 500 atmospheres, with a mean absolute deviation of 2.35 percent. This equation was used to compute

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1/ Supervisory chemical research engineer.

2/ Chemical engineer.

3/ Chemical research engineer.
All authors are with the Division of Helium, Branch of Research and Laboratory Services, Bureau of Mines, Amarillo, Tex.

thermal conductivity values of gaseous nitrogen for 47 pressures, 1 to 240 atmospheres, and 110 temperatures, 133° to 740° K, which are common to conditions encountered in Bureau of Mines helium purification processes.

Isobaric heat capacity, C_P, and viscosity, $\eta_{T,P}$, values from previous work were combined with the present thermal conductivity, $\lambda_{T,P}$, values to compute Prandtl numbers, $C_P \eta_{T,P} / \lambda_{T,P}$, of nitrogen. Tabular values of Prandtl numbers are presented for 49 pressures, 1 to 240 atmospheres, and 75 temperatures, 133° to 740° K.

It is estimated that uncertainties are ±5 percent in the tabulated thermal conductivity values and ±15 percent for the computed Prandtl numbers. However, the uncertainty may rise to ±10 percent for thermal conductivity values and to ±30 percent for Prandtl numbers as the critical conditions of nitrogen are approached.

INTRODUCTION

The Bureau of Mines uses modified Claude-type nitrogen refrigeration cycles for both helium extraction and purification processes. At the present time, nearly all liquid helium produced commercially is made in liquefiers which utilize a nitrogen refrigeration cycle. Nitrogen refrigeration cycles are also used in other areas of technology.

The design of an economical nitrogen refrigeration cycle depends upon striking a proper balance between heat exchanger and compression services. The engineer charged with equipment design and evaluation requires an extensive knowledge of the variation of the thermophysical properties of nitrogen over a broad range of pressures and temperatures. An accurate

knowledge of the thermal conductivity behavior of nitrogen must be known at all operating conditions encountered in the refrigeration cycle heat exchangers. Low-pressure thermal conductivity values of nitrogen over a broad range of temperatures are fairly abundant, and most of the available data have been systematically analyzed and compared. However, at the high pressures and low temperatures encountered in nitrogen refrigeration cycles, data that can be found are of a research nature and require correlation to be of value to engineers.

This report presents a method for the general correlation and prediction of the thermal conductivity values of compressed gaseous nitrogen over the practical range of pressures and temperatures encountered in the gas-to-gas heat exchangers of nitrogen refrigeration cycles. The temperature dependency of the low-density thermal conductivity values of nitrogen is correlated with the Keyes' equation,

$$\lambda_T^\circ = aT^{1/2} \Big/ \left(1 + bT^{-1}\, 10^{-12/T}\right) , \qquad (1)$$

and the effect of pressure on the thermal conductivity behavior of nitrogen is generalized with the residual thermal conductivity, $\left(\lambda_{T,P} - \lambda_T^\circ\right)$, as a function of the thermal pressure coefficient, $\left(\frac{\partial P}{\partial T}\right)_V$, and two parameters, α and β,

$$\lambda_{T,P} - \lambda_T^\circ = \alpha \left[\left(\frac{\partial P}{\partial T}\right)_V\right]^\beta . \qquad (2)$$

The design and analyses of all types of heat exchangers require a knowledge of the heat transfer coefficient for a given geometry and specified flow conditions. In calculating convective heat transfer between fluids flowing past a solid surface, the dimensional equation

$$Nu = c(Re)^m (Pr)^n , \tag{3}$$

where c, m, n = constants,

$$Nu = \frac{\bar{h}_c L}{\lambda} = \text{Nusselt number},$$

$$Re = \frac{\rho \dot{\nu} L}{\eta} = \text{Reynolds number},$$

and $$Pr = \frac{C_P \eta}{\lambda} = \text{Prandtl number},$$

is usually employed.

The average convective-heat-transfer coefficient, $\bar{h}_c$, is a function of six variables

L = significant length such as tube diameter,

$\dot{\nu}$ = velocity of the fluid,

ρ = density of the fluid,

C_P = isobaric specific heat of the fluid,

η = shear viscosity of the fluid,

and λ = thermal conductivity of the fluid.

L and $\dot{\nu}$ are intrinsic to the geometry of the heat-transfer surface and the flow condition imposed. Therefore, for a given heat-transfer geometry and flow, the nature of change in $\bar{h}_c$ is due to the specific

dependence of η, ρ, λ, and C_P on temperature and pressure. The variation of thermodynamic properties and viscosity of nitrogen with temperature and pressure has been evaluated in other programs of the Bureau of Mines (39-41),[4/] and these physical properties can be combined

4/ Underlined numbers in parentheses refer to items in the list of references at the end of this report.

with the present thermal conductivity values to form a work basis for engineering efforts to improve the design and evaluate the efficiency of nitrogen refrigeration cycles.

Isobaric heat capacity, C_P, (39), viscosity, $\eta_{T,P}$, (40), and the thermal conductivity, $\lambda_{T,P}$, values of this work were used to compute Prandtl numbers of nitrogen. Tabular values of Prandtl numbers are presented for 49 pressures, 1 to 240 atmospheres, and 75 temperatures, 133° to 740° K.

ACKNOWLEDGMENTS

The authors extend their appreciation to E. P. Fisher, formerly of the Helium Research Center, who helped by plotting some of the graphs.

LOW-DENSITY THERMAL CONDUCTIVITY OF NITROGEN

There is no generalized procedure for calculating thermal conductivity values of dilute diatomic gases. At the present time, correlation of low-pressure thermal conductivity values for a given range of temperatures can be handled by three methods:

1. The Chapman-Enskog (5, 13) kinetic theory expressions for computing the thermal conductivity of a monatomic gas can be used and the Eucken correction (13) applied to the results to approximate the thermal conductivity of dilute diatomic gases.

2. The thermal conductivity of dilute diatomic gases can be computed from the more elaborate and complex kinetic theory of heat conductivity of polyatomic and polar gases of Mason and Monchick (22) if good experimental relaxation times for the internal degrees of freedom in the molecule are available.

3. The available experimental data can be represented by a purely empirical equation.

Childs and Hanley (7) used method 1 to calculate the low-density thermal conductivity values, λ_T°, of nitrogen for the temperature range of about 100° to 1,200° K and found that this method did not give satisfactory results. Reid and Sherwood (30) say that the best theoretical method to determine thermal conductivity for polyatomic gases is that of Mason and Monchick (22), or method 2. Mason and Monchick computed thermal conductivity values for nitrogen by using their equations and a rotational relaxation time based on the formulation of Parker, cited in their paper, and they said of their results, "The present calculations seem to agree with the experimental results as well as the experimental results agree among themselves." Unfortunately, reported values for the

low-density thermal conductivity of nitrogen vary by as much as 12 percent even when data are obtained by using the same experimental method. Also, among the different techniques used for the measurement of the rotational relaxation number, values differ by a factor of 3 or more. Therefore, to differentiate which of the above methods is most accurate by comparison of the available experimental data with computed results is utterly impractical at the present time.

Keyes (15) found that λ_T° values of nitrogen could be represented by equation 1, and Keyes and Vines (19) showed that experimental λ_T° values of nitrogen, in the temperature range 0° to 900° C, of 12 investigators were well represented by equation 1. Childs and Hanley (7) correlated λ_T° values of nitrogen from 7 sources, 80° to 1,200° K, with a fourth degree power series in T and obtained an adequate representation of the data they used.

The simple form of the Keyes' equation or a simple polynomial to correlate the temperature dependency of λ_T° values of nitrogen is much more attractive for engineering use than either methods 1 or 2 above.

Experimental low-pressure thermal conductivity values of nitrogen have been collected, organized, critically evaluated, and compiled by the Thermophysical Properties Research Center, Lafayette, Indiana. The TPRC values for the thermal conductivity of nitrogen at atmospheric pressure for the temperature range 50° to 3,500° K are those recommended by the National Standard Reference Data System of the National Bureau of Standards (29). The accuracy of the NBS tabulated values is assessed by

Powell, Ho, and Liley (29) to be 2 percent for temperatures below about 350° K and 5 percent for temperatures from 350° to 1,200° K. Vargaftik and Zimina (36) have also analyzed nitrogen thermal conductivity data available at pressures below and to 1 atmosphere where λ_T° is assumed to be independent of pressure for the temperature range 0° to 1,106° C. They attempted to correct λ_T° measurements for the "temperature jump" effect before considering them for correlation with their own corrected experimental data which is within the temperature range 30.6° to 861° C.

Vargaftik and Zimina (36) used a hot-wire type thermal conductivity cell (34) for their measurements, and their correlation is based almost exclusively on results obtained by this method. In the 0° to 1,100° C temperature range of values they recommend for the thermal conductivity of nitrogen, there are data obtained from coaxial-cylinder and parallel-plate cells (34) which are essentially free of the "temperature jump" effect and which they did not consider. For this reason, their recommendations (36) differ from those of NBS (29), and at temperatures above 350° K, Vargaftik and Zimina (36) values tend to be higher than those recommended by Powell, Ho, and Liley in NSRD-NBS-8 (29). At 1,000° K Vargaftik's value for the thermal conductivity of nitrogen is 3 percent higher than the NBS (29) value.

Experimental low-density nitrogen thermal conductivity data from sources (1-2, 4, 6, 8, 11, 15-18, 20, 23, 25-26, 31-33, 36-38, 42) and thermal conductivity values tabulated by NBS (29) for the temperature range 80° to 1,200° K were fitted to equation 1 and to power series in T through the fifth degree by the method of least squares.

The Keyes' (15, 19) type equation

$$\lambda_T^\circ = 24.237\,\sqrt{T} \,/\, \left(1.0 + \frac{207.73}{T}\,10^{-12/T}\right) , \qquad (4)$$

where λ_T° = thermal conductivity of nitrogen, μj/cm sec °K,

and T = absolute temperature, °K,

was found to be more representative of the data than any of the polynomials tested. Figure 1 shows deviations of various investigators' experimental

FIGURE 1. - Low-Density Thermal Conductivity Deviation Plot for Nitrogen.

results from computed values obtained from equation 4 and a smooth "best fit" curve for deviations of the NBS (29) recommended values, not shown, for the thermal conductivity of nitrogen.

Deviation, percent, in figure 1 is represented by

$$\text{Deviation, percent} = [(\text{Exp.} - \text{Calc.}) / \text{Calc.}] \times 100 , \qquad (5)$$

where Exp. = the experimental value reported by an investigator,

and Calc. = the value computed in this work.

DENSE-GAS THERMAL CONDUCTIVITY OF NITROGEN

No systematic approach to compute the thermal conductivity coefficients of dense gases is known as yet, and there appears to be no accepted theory upon which to base estimation techniques.

The kinetic theory of dense gases and liquids (13) does not, at present, enable the accurate calculation of thermal conductivity coefficients of diatomic gases at high pressures.

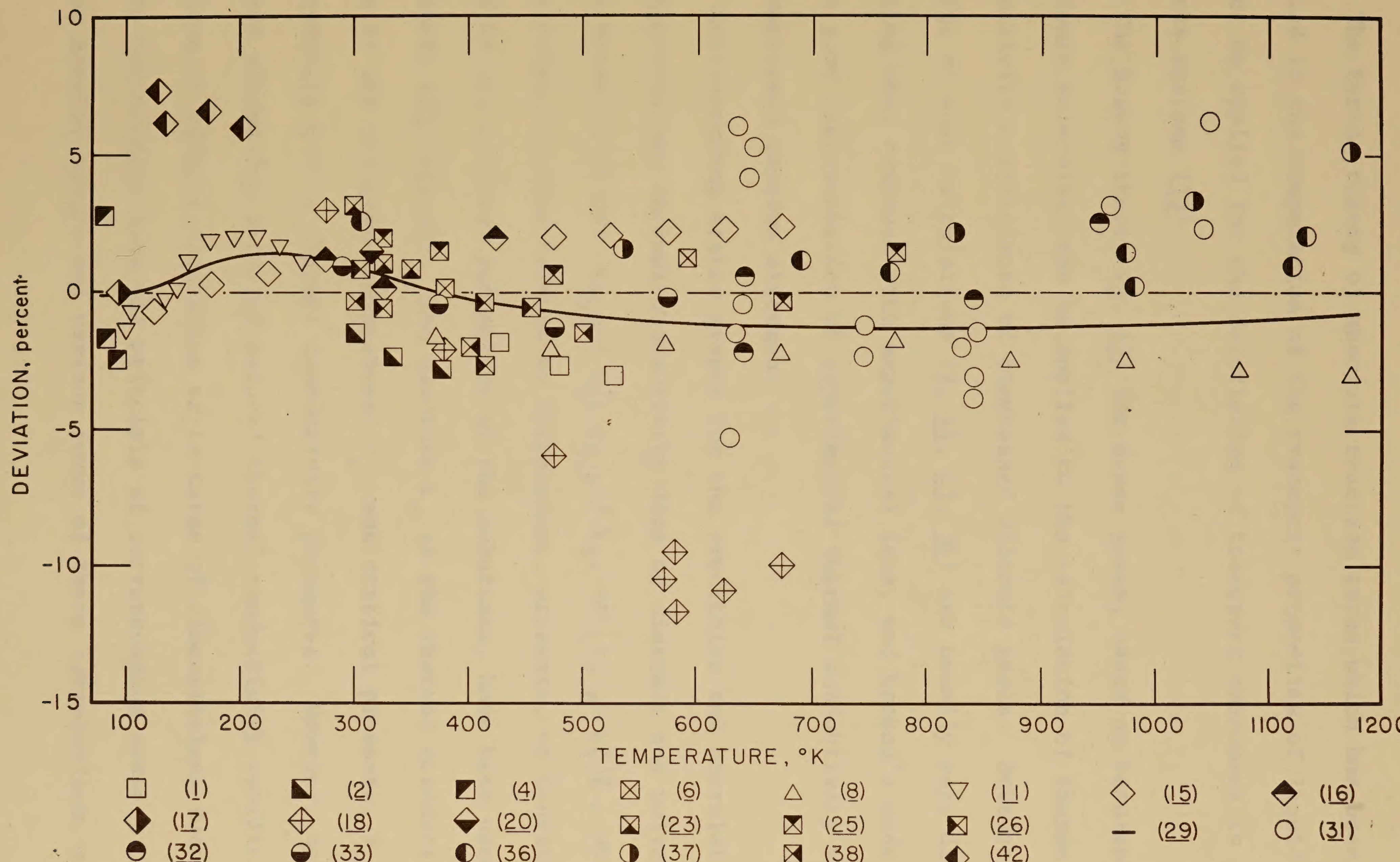

FIGURE I.—Low-Density Thermal Conductivity Deviation Plot for Nitrogen.

The Eyring theory of absolute reaction rates which has been adapted to the computation of the transport properties of liquids cannot be applied for the description of transport phenomena in gaseous systems (13).

The Enskog theory (5, 13) for dense gases, based on hard-sphere monatomic molecules, can be applied to the calculation of thermal conductivity coefficients of compressed diatomic gases. However, the results of such calculations (9, 14, 23, 34) are usually very disappointing when compared with experimental data, and Enskog's model is not a good representation of experimental thermal conductivity values of compressed gaseous nitrogen.

Corresponding states graphs for the prediction and correlation of high-pressure thermal-conductivity data of diatomic and polyatomic gases based on either $\lambda_{T,P} / \lambda_T^\circ$, $\lambda_{T,P} / \lambda_c$, or $\left(\lambda_{T,P} - \lambda_T^\circ\right)\xi$, wherein these properties are related to temperature, pressure, or density reduced by the critical parameters of the substance, have been used by engineers (21, 24, 30). The quantity λ_c is the thermal conductivity value at the critical temperature, T_c, and critical pressure, P_c. The quantity ξ is a thermal conductivity parameter. However, no general scheme for defining reduced thermal conductivity coefficients in terms of reduced properties or in terms of dimensionless functional groups has emerged from the principle of corresponding states. Because of the general nature and various forms of these correlations, predicted

thermal conductivities may deviate from measurement by as much as 70 percent (21), and predicted thermal conductivity values are particularly unreliable at low temperatures as critical conditions are approached.

Tsederberg (34, Ch. IV) discusses 9 different methods for correlating the thermal conductivity data for gases under pressure. He recommends the Vargaftik equation,

$$\lambda_{T,P} = \lambda_T^\circ + B\gamma^n , \tag{6}$$

where $\lambda_{T,P}$ = thermal conductivity of the compressed gas,

λ_T° = thermal conductivity of the gas at atmospheric pressure,

γ = specific weight of the gas,

and B and n = constants,

as being the most reliable.

Borovik (3) and Johannin (14) summarized their thermal conductivity measurements in terms of Amagat densities. Residual thermal conductivity, $\left(\lambda_{T,P} - \lambda_T^\circ\right)$, has been assumed to be a monotonic function of density, ρ (11), and of reduced density, ρ_r (24). However, this unique dependence of $\left(\lambda_{T,P} - \lambda_T^\circ\right)$ or $\lambda_{T,P}$ on ρ is not observed at low temperatures and moderate pressures (3, 11) but, instead, isometric experimental thermal conductivity data are temperature dependent and are arranged on divergent isotherms.

Other empirical relations (16, 18, 24-25) for the prediction of the thermal conductivity behavior of compressed nitrogen have been used, but most of these equations are not satisfactory for extrapolation beyond a given range of experimental data.

Golubev (10) introduced the thermodynamic quantity $\left(\frac{\partial P}{\partial T}\right)_V$ to replace density in the correlation of residual viscosity, and Wood and Boone (40) used this concept to generalize the viscosity behavior of the helium-nitrogen system from 133° to 740° K for pressures to 240 atmospheres. The relative change in the thermal conductivity of nitrogen with pressure is similar to the relative change in the viscosity of nitrogen with pressure, and these transport properties for the compressed gas vary by several hundred percent from the low-density values as critical conditions are approached. Therefore, an extension of Golubev's (10) relationship for residual viscosity to residual thermal conductivity correlation appears appropriate, and equation 2,

$$\lambda_{T,P} - \lambda_T^\circ = \alpha \left[\left(\frac{\partial P}{\partial T}\right)_V \right]^\beta ,$$

and equation 6 of Vargaftik,

$$\lambda_{T,P} - \lambda_T^\circ = B\gamma^n ,$$

were investigated.

Thermal pressure coefficients, $\left(\frac{\partial P}{\partial T}\right)_V$, and specific weight values, $\gamma = g/cm^3$, were derived from the equation of state of Wood and coworkers (41), and residual thermal conductivities, $\Delta\lambda = \left(\lambda_{T,P} - \lambda_T^\circ\right)$, were obtained from experimental thermal conductivity data for pressures below 300 atmospheres. If an investigator gave λ_T° values, these values were used in conjunction with his higher pressure data to obtain $\Delta\lambda$ values; otherwise, applicable λ_T° values computed from equation 4 were used to compute

residual conductivities. Ziebland and Burton (42) presented low-density thermal conductivity values, but these data are at temperatures which do not coincide with their higher pressure results. Because their experimental λ_T° values are not in good agreement with results obtained from equation 4 (see figure 1), applicable λ_T° values obtained from a graph of their low-density thermal conductivity measurements were used to obtain $\Delta\lambda$ values.

The nonlinear Golubev equation, equation 2, can be readily reduced to a linear form for least-squares treatment by treating residuals, r, as

$$r = \log \alpha + \beta \log \left(\frac{\partial P}{\partial T}\right)_V - \log \left(\lambda_{T,P} - \lambda_T^\circ\right) , \tag{7}$$

and the nonlinear equation of Vargaftik, equation 6, can be treated in a like manner,

$$r = \log B + n \log \gamma - \log \left(\lambda_{T,P} - \lambda_T^\circ\right) , \tag{8}$$

but this procedure of evaluating α, β, B, and n so that Σr^2 is a minimum is inappropriate and would be correct only for a constant absolute error in $\log \left(\lambda_{T,P} - \lambda_T^\circ\right)$; that is, for a constant percentage error in $\left(\lambda_{T,P} - \lambda_T^\circ\right)$, which is very unlikely. A general computer program for solving nonlinear regression problems written by Grout (12) was used to evaluate α and β in the Golubev relationship and B and n in the Vargaftik equation. Estimating parameters for Grout's computer program were obtained in a linear least-squares treatment of $\left(\lambda_{T,P} - \lambda_T^\circ\right)$

values as indicated by equations 7 and 8. Estimating parameters are improved in the nonlinear least-squares program by the Newton-Raphson or Gauss-Newton method of iteration. Convergence was assumed when Σr^2 values of successive approximations differ by 10^{-16} or less in the nonlinear least-squares program (12).

The parameters α and β in the Golubev equation and B and n in the Vargaftik equation were computed from individual thermal conductivity isotherms (to see if the parameters were temperature-dependent), from the combined data of individual investigators, and from the total data set. A great variation in the magnitude of the B parameter was found, and in general the Vargaftik equation did not represent the experimental data as well as the Golubev relationship.

Residual thermal conductivity, $\Delta\lambda$, values obtained from 16 sources (3, 9, 11, 14, 16-21, 23-25, 33, 35, 42) were considered in computing α and β values for the Golubev equation. The experimental data of Stoliarov and coworkers (33) had to be rejected from consideration because convergence could not be obtained in the iteration processes employed in the nonlinear least-squares program (12), and values α and β for these investigators could not be evaluated. Stoliarov and coworkers smoothed their experimental data and presented a tabulation (table 3 in their paper) of thermal conductivity values at six pressures, 1, 100, 200, 300, 400, and 500 kg/cm^2, for four isotherms, 15°, 100°, 200°, and 300° C. The Golubev parameters, α and β, computed from their smoothed data were found to be temperature dependent and were not used.

It appears that a number of irregularities in their experimental data were smoothed out in preparing table 3 in their paper. The thermal conductivity measurements of Michels and Botzen (23) in the dense gas region are known to be consistently higher than measurements of other investigators (14, 24, 34), and their measurements to 200 atmospheres only were used in obtaining α and β values.

Four-hundred residual thermal conductivity values were used to obtain the "best" overall values of α and β for nitrogen. The non-linear regression analyses yielded

$$\left(\lambda_{T,P} - \lambda_T^\circ\right) = 131.17011 \left[\left(\frac{\partial P}{\partial T}\right)_V\right]^{0.898043} , \qquad (9)$$

where $\left(\lambda_{T,P} - \lambda_T^\circ\right)$ = residual viscosity, μj/cm sec °K,

and $\left(\frac{\partial P}{\partial T}\right)_V$ = atm / °K.

Table 1 shows the data distribution and average absolute percentage deviations between the computed and experimental thermal conductivity values of various investigators. Table 1 has the inadequacy of not showing the spread or dispersion of quantities used to compute the mean absolute deviation. Therefore, table 2 is provided to show the maximum deviations between computed and experimental thermal conductivities for nitrogen. For all comparisons in tables 1 and 2, computed thermal conductivity values, $\lambda_{T,P}$, were obtained by using λ_T° values computed from equation 4 in equation 9.

TABLE 1. - page 18

TABLE 1. - Data distribution and error analysis

Source of data	Temperature range, °K	Pressure range, atmospheres	No. of points	$\frac{\Sigma\lvert\text{Pct Dev}\rvert}{N}$ 1/
Borovik (3)	132.65-170.65	24.4- 99.0	13	4.77
Gilmore and Comings (9)	348.15	1 -500	8	2.34
Golubev and Kalsina (11).	133.15-273.15	1 -300	180	1.31
Johannin (14)	348.15-973.15	1 -391	35	1.86
Keyes (16).	323.15-423.15	1 -143.4	7	.42
Keyes (17).	273.15	7.6- 10.6	2	.26
Keyes and Sandell (18).	273.15-622.0	1 -151.7	37	4.34
Keyes and Vines (19).	412.85-620.75	(2/) -428.70	36	.76
Lenoir and Comings (20)	314.26	1.0-205.7	13	.78
Lenoir, Junk, and Comings (21). . . .	325.93	1.0-216.7	13	.70
Michels and Botzen (23)	298.15-348.15	1 -453	44	5.54
Misic and Thodos (24)	295.35-323.65	1 -314.7	23	1.18
Nuttall and Ginnings (25)	323.15-773.15	.7-100	18	1.20
Peterson, Hahn, and Comings (27). . .	348.15	50 -500	5	2.39
Stoliarov and others (33)	285.65-571.15	1.0-483.9	22	3.78
Uhlir (35).	132.6 -184.3	33.3- 67.3	6	4.57
Ziebland and Burton (42).	131.2 -202.5	1.0-134.0	47	4.69
Total, all observations			509	2.35

1/ Mean absolute percent deviation.

2/ Low-density thermal conductivity values obtained by extrapolation from values at higher pressures.

TABLE 2. - page 19

TABLE 2. - Maximum deviations between computed and experimental thermal conductivities

Source of data	Temperature, °K	Pressure, atm	$\lambda_{Exp.}$, µJ/cm sec °K	$\lambda_{Comp.}$, µJ/cm sec °K	Deviation, percent
Borovik (3)	132.65	24.4	188.3	168.79	11.56
Gilmore and Comings (9)	348.15	150	353.5	364.56	-3.03
Golubev and Kalsina (11)	133.15	50	386.60	419.78	-7.90
Johannin (14)	473.15	100	393	407.35	-3.52
Keyes (16)	423.15	1	348.1	342.09	1.76
Keyes (17)	373.15	7.6	243.5	242.76	.30
Keyes and Sandell (18)	622.0	49.8	418.8	471.89	-11.25
Keyes and Vines (19)	522.55	175.20	446.3	455.54	-2.01
Lenoir and Comings (20)	314.26	196.1	386.19	378.55	1.49
Lenoir, Junk, and Comings (21)	325.93	1.0	280.4	276.70	1.34
Michels and Botzen (23)	298.15	377	561	492.06	14.01
Misic and Thodos (24)	323.65	88.3	310.0	321.01	-3.43
Nuttall and Ginnings (25)	773.15	100	579.4	556.46	4.12
Peterson, Bohn, and Comings (27)	348.15	50	300.0	316.12	-5.10
Stolyarov and others (33)	376.15	96.78	321.7	353.54	-9.01
Uhlir (35)	182.1	67.2	460.2	399.05	15.32
Ziebland and Burton (43)	136.2	50.3	453.96	357.41	27.01

TABLE 2. - Maximum deviations between computed and experimental thermal conductivities

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Borovik (3).	132.65	24.4	188.3	168.79	11.56
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Keyes (16)	423.15	1	348.1	342.09	1.76
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Keyes and Sandell (18)	622.0	49.6	418.8	471.89	-11.25
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Uhlir (35)	142.1	67.2	460.2	399.05	15.32
Ziebland and Burton (42)	136.2	50.3	453.96	357.41	27.01

Discrepancies between computed and experimental higher pressure thermal conductivity values can be characteristic of the deviations between low-density experimental results and values computed from equation 4, or the failure of the relationship $\alpha \left[\left(\frac{\partial P}{\partial T}\right)_V\right]^\beta$ to account in full for the excess thermal conductivity due to pressure, or a combination of these factors. Also, discrepancies between computed and experimental values can be ascribed to errors in the basic thermal conductivity measurements. Tsederberg (34, Ch. I) discusses five factors that introduce errors in thermal conductivity measurements. These factors are:

1. Heat transfer into or from the apparatus.
2. Heat transfer by radiation.
3. Temperature jumps at the boundary between equipment and the test gas.
4. Convective heat transfer.
5. Eccentricity between parts of the apparatus.

In the region of the critical state and at high densities, the tendency for free-convective heat transfer to occur in a thermal conductivity apparatus is very great. Borovik (3) observed that the apparent thermal conductivity values, $\lambda'_{T,P}$, he obtained from his parallel-plate apparatus were dependent upon the magnitude of the temperature difference, ΔT, between the measuring plates of his apparatus. In an

effort to exclude the effect of free-convective heat transfer from his measurements, he plotted $\lambda'_{T,P}$ quantities versus corresponding ΔT's and made a linear extrapolation to zero temperature difference to obtain his reported thermal conductivity values. Uhlir (35) and Ziebland and Burton (42) have found fault with Borovik's method for correcting for convective heat transfer in his experiments, because his method is in contrast to the criterion (9, 14, 20, 24, 34-35, 42) usually considered in an evaluation of the probability of convective heat transfer in thermal conductivity determinations. This criterion will be discussed later. The very large deviations shown in table 2 for the results of Borovik (3), Uhlir (35), and Ziebland and Burton (42) are for conditions where convection was said to be likely or was observed by the investigator.

Table 1 shows the mean absolute percent deviation to be 4.77 for the 13 points of Borovik (3). However, two points in his data account for 37 percent of the overall discrepancy between computed and experimental values. His data point at 145.7° K and 49.9 atm is 11.38 percent higher than our computed value, and his other data point with a large deviation with respect to the computed value is given in table 2. It is assumed these points were obtained at conditions which required large corrections for free convection. A $\lambda'_{T,P}$ versus ΔT graph in Borovik's paper shows $\lambda'_{T,P}$ values at zero temperature difference are as much as 30 to 40 percent smaller than $\lambda'_{T,P}$ values measured at finite temperature differences.

The entry in table 2 for Uhlir (35) accounts for 56 percent of the overall discrepancy between computed and experimental values given in table 1. Uhlir says that convection was likely in the region in which this experimental point was obtained.

The low-density results of Ziebland and Burton (42) depart from results obtained from equation 4 by about 6 percent (see figure 1), and discrepancies between computed and experimental higher pressure thermal conductivity values are for the most part characteristic of the low-density results. The concentration of $\triangle\lambda$ values derived from their results about the regression line $\alpha\left[\left(\frac{\partial P}{\partial T}\right)_V\right]^\beta$ is fairly good at high temperatures. However, in the region of the critical state of nitrogen, several residual thermal conductivity values were widely dispersed with respect to the regression line.

The low-density thermal conductivity values of Keyes and Sandell (18) depart from the results of other investigators as the temperature increases (see figure 1), and at about 600° K their values are 10 to 12 percent low. The discrepancies between computed values and their experimental higher pressure thermal conductivity values are for the most part characteristic of the low-density results. Residual thermal conductivity values derived from their data do not conflict in any essential way with the general results obtained from the empirical model $\alpha\left[\left(\frac{\partial P}{\partial T}\right)_V\right]^\beta$. Their

discordant results are in part due to the absence of a guard heater in their apparatus and their failure to account for increased heat losses from their thermal conductivity apparatus at higher temperatures. For additional details regarding other deficiencies in their method, see Tsederberg's book (34).

The percentage deviation given in table 2 for Gilmore and Comings (9) is very close to the 3 percent accuracy they estimated for their results.

Golubev and Kalsina (11) treated their experimental data in the coordinates of $\left(\lambda_{T,P} - \lambda_T^{\circ}\right)$ versus density, ρ, and present smoothed and interpolated results only. They say their experimental data are located on a common curve with the exception that some of their nitrogen points near the critical temperature were above the common curve. For the 133.15° K isotherm, their thermal conductivity values at 40 and 70 atmospheres, the closest points concomitant to their 50 atmosphere value, given in our table 2, have deviations between computed and experimental values of -3.46 and +4.56 percent, respectively, and their table entry at 50 atmospheres could be in error. If this assumption is correct, the +4.56 percent deviation at 70 atmospheres would be the largest for their data.

Nuttall and Ginnings (25) observed that their apparent thermal conductivity, $\lambda'_{T,P}$, measurements at 100 atmospheres pressure changed with the amount of electrical power supplied heaters in a parallel-plate apparatus. In an effort to free their results of the convective heat

transfer error, they extrapolated observed $\lambda'_{T,P}$ quantities to zero power input and reported "zero" power intercept values as the "true" thermal conductivity values of nitrogen.

Johannin (14) has shown that the thermal conductivity values of Michels and Botzen (23) are larger than those of other investigators for pressures greater than 100 atmospheres. Johannin suggests that Michels and Botzen's results are in error due to free convection because disparities increase systematically with increasing pressure.

Neither the experimental nor smoothed thermal conductivity values of Stoliarov and coworkers (33) are satisfactorily correlated by the Golubev relationship. Their values are, in general, smaller than thermal conductivity values computed in this work, and very large deviations (-2.00 to -9.52 percent) are predominant for both their measured and smoothed data at pressures near 100 kg/cm^2 at all temperatures. Also, their thermal conductivity values are not satisfactorily correlated by the equation of Vargaftik, equation 6.

The design of an apparatus for the determination of thermal conductivity values of a gas should preclude the possibility of free-convective heat transfer. The design criterion usually applied is that the product of the Grashof and Prandtl numbers be less than some given number, usually $(Gr \circ Pr) \leq 1{,}000$. This standard is generally referred to as the Rayleigh (9, 42) criterion or the Kraussold relation (14, 20, 24, 34-35). The Rayleigh number is equal to the product of the Prandtl and Grashof

numbers. The dimensionless Grashof number is defined as

$$Gr = \varphi\, g\, \rho^2\, L^3\, \Delta T/\eta^2 \, , \tag{10}$$

where $\varphi = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$ = coefficient of cubical expansion,

g = acceleration of gravity,

ρ = the density,

L = thickness of the test gas layer,

ΔT = applied temperature difference,

and η = shear viscosity.

The dimensionless Prandtl number is defined as

$$Pr = C_p\, \eta/\lambda \, , \tag{11}$$

where C_P = isobaric specific heat per unit mass,

η = shear viscosity,

and λ = thermal conductivity.

The Rayleigh number is

$$Ra = \varphi\, g\, \rho^2\, C_p\, L^3\, \Delta T/\lambda \eta \, . \tag{12}$$

Ziebland and Burton discuss the Rayleigh criterion, but they lacked the pertinent physical data to apply the criterion to their measurements. Uhlir (35) estimated viscosity, η, values from hard-sphere theory, and C_P, φ, and ρ values for argon and nitrogen from the thermodynamic properties of hydrocarbons at corresponding states.

He rightfully declares his calculations of the Rayleigh modulus cannot be very accurate. For his apparatus, his calculations show convection is likely in an area on a λ versus T graph where the boundaries are reduced pressure, $\frac{P}{P_c}$, from 7/8 to 2 and temperature from T_c to about 20° K above the critical temperature, T_c. In the area delineated by Uhlir for convection, the agreement between computed values and the experimental thermal conductivity data of investigators (3, 35, 42) is poor, and experimental values are, in general, larger than the computed values. For those investigators (9, 14, 20, 24) who designed their experiments for Ra $\leq$ 1,000, the agreement between computed and experimental values is, in general, within the inherent accuracy of the measurements, ±3 percent or less.

Figure 2 shows computed thermal conductivities of nitrogen. A

FIGURE 2. - Thermal Conductivity of Nitrogen.

common characteristic of gases in the vicinity of the critical region is a sharp rise in the thermal conductivity with increasing pressure. The computed results cannot be compared quantitatively for each isobar because of lack of sufficient experimental data. However, the variation of thermal conductivity along isobars conforms to this generalization and illustrates further the ability of the prediction equation to represent the behavior of a real gas.

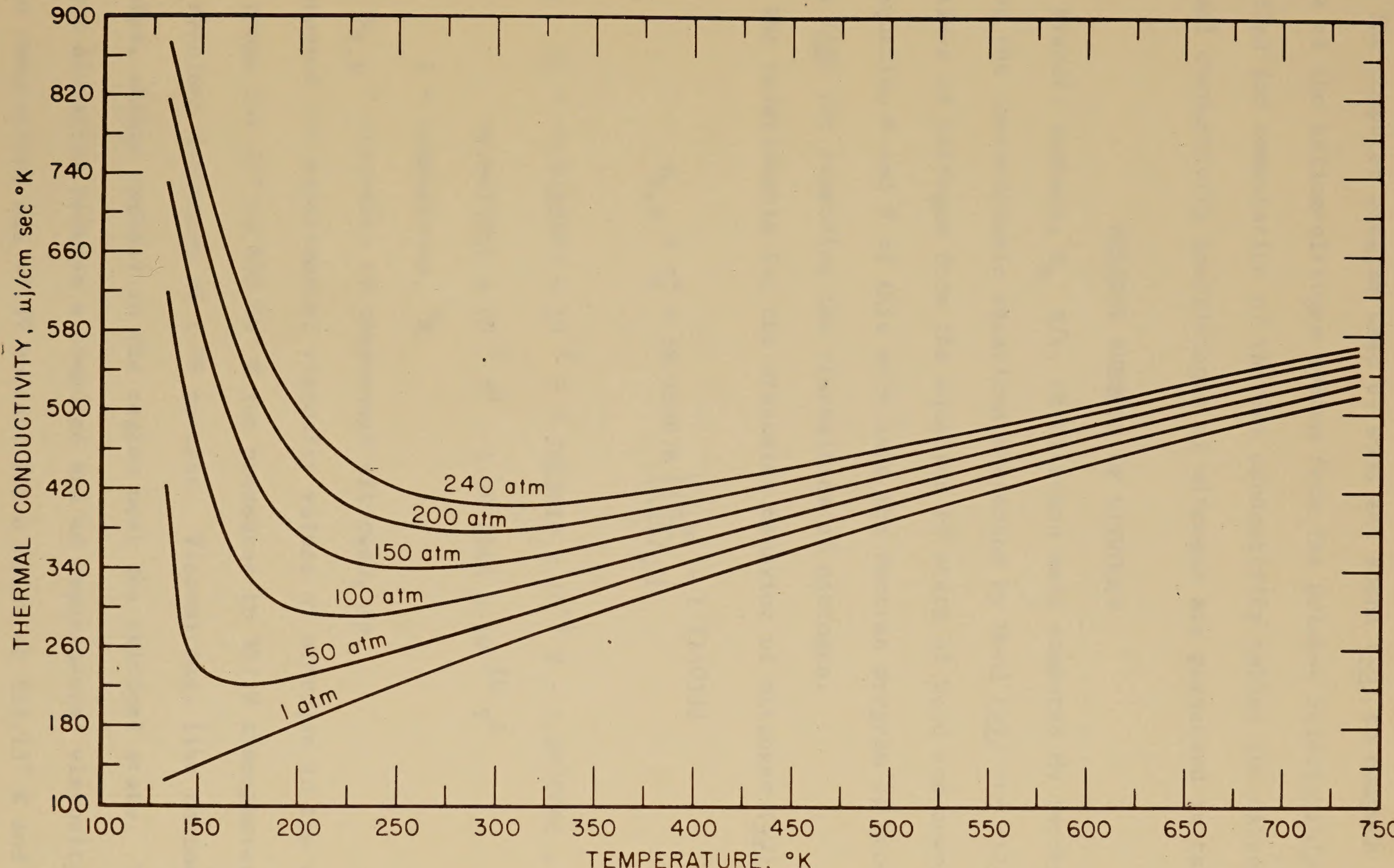

FIGURE 2. – Thermal Conductivity of Nitrogen.

The computer program used by Wood and Boone (40) to compute viscosities of the helium-nitrogen system from the Golubev relationship was modified for computation of thermal conductivity tables for nitrogen. Thermal conductivity coefficients of nitrogen are presented in table 3.

PRANDTL NUMBERS OF NITROGEN

Prandtl numbers, $C_P\,\eta/\lambda$, of nitrogen were computed by incorporating the thermodynamic equations presented by Wood (39) for calculating C_P values of nitrogen from the equation of state of Wood and coworkers (41) and equation 4 and 9 of this work into the Fortran program of Wood and Boone (40) for computing the viscosities of nitrogen.

The relationship for the viscosity behavior of nitrogen (40),

$$\eta_{T,P} = \eta_T^\circ + 58.265976\left[\left(\frac{\partial P}{\partial T}\right)_V\right]^{1.1160332}, \tag{13}$$

where $\eta_T^\circ = -8.9188690 \times 10^{-1} + 7.7622418 \times 10^{-1}\,T - 7.2970066 \times 10^{-4}\,T^2$
$+4.9473812 \times 10^{-7}\,T^3 - 1.3971248 \times 10^{-10}\,T^4$,

T = temperature, °K,

and $\eta_{T,P}$ = viscosity of compressed nitrogen, μp,

represented 576 experimental viscosity values of nitrogen in the temperature range 131.15° to 933.46° K for pressures to 547.8 atmospheres with a mean absolute deviation of 1.09 percent. Viscosities, like thermal conductivities, change rapidly in the region near the critical state. The maximum deviation between a computed and an experimental viscosity value at low temperature was +7.59 percent for a point at 132.15° K and 248.92 atmospheres.

TABLE 3 - 5 pages - pg #s 28, 29, 30, 31, 32

TABLE 3. - THERMAL CONDUCTIVITY OF NITROGEN

μJ/CM SEC °K

T, DEG K	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154
P, ATM	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1	125	126	127	127	128	129	130	131	132	133	133	134	135	136	137	138	139	139	140	141	142	143
5	131	131	132	133	134	135	136	136	137	138	139	140	140	141	142	143	144	144	145	146	147	148
10	138	139	140	140	141	142	143	143	144	145	146	146	147	148	149	149	150	151	152	152	153	154
15	147	148	148	149	149	150	151	151	152	153	153	154	154	155	156	156	157	158	158	159	160	161
20	158	158	158	159	159	159	160	160	161	161	162	162	163	163	164	164	165	165	166	167	167	168
25	170	170	170	170	170	171	171	171	171	171	171	172	172	172	173	173	173	174	174	175	175	176
30	188	187	186	185	185	184	184	184	183	183	183	183	183	183	183	183	183	184	184	184	184	184
35	213	210	207	205	203	202	200	199	198	198	197	196	196	195	195	195	195	195	194	194	194	194
40	263	250	241	235	230	226	223	220	218	216	214	213	212	210	209	209	208	207	207	206	206	206
45	368	337	309	288	274	263	255	249	244	240	236	233	231	229	227	225	224	222	221	220	219	218
50	423	402	380	358	337	318	303	290	280	272	265	260	255	251	248	245	242	240	238	236	234	233
55	458	441	424	406	389	371	354	338	324	312	302	293	285	279	273	268	264	261	257	254	252	250
60	486	471	456	441	425	410	395	380	366	352	340	329	319	310	302	295	289	284	280	275	272	268
65	509	496	482	468	454	441	427	413	400	387	374	363	352	342	332	324	317	310	304	298	293	289
70	529	517	504	491	479	466	453	441	428	416	404	393	382	371	361	352	344	336	329	322	316	311
75	548	536	524	512	500	488	476	464	452	441	430	418	408	397	388	378	369	361	353	346	339	333
80	564	553	542	530	519	507	496	485	474	463	452	441	431	421	411	402	393	384	376	368	361	354
85	580	569	558	547	536	525	514	504	493	482	472	462	452	442	432	423	414	405	397	389	382	375
90	594	584	573	563	552	542	531	521	511	500	490	480	471	461	452	443	434	425	417	409	401	394
95	608	598	588	578	567	557	547	537	527	517	507	497	488	479	469	461	452	443	435	427	419	412
100	621	611	601	591	582	572	562	552	542	532	523	513	504	495	486	477	469	460	452	444	436	429
105	634	624	614	605	595	585	576	566	556	547	538	528	519	510	502	493	484	476	468	460	453	445
110	646	636	627	617	608	598	589	579	570	561	552	543	534	525	516	508	499	491	483	475	468	460
115	658	648	639	629	620	611	602	592	583	574	565	556	547	539	530	522	513	505	497	490	482	475
120	669	660	650	641	632	623	614	605	596	587	578	569	560	552	543	535	527	519	511	503	496	488
125	680	671	662	652	643	634	625	616	607	599	590	581	573	564	556	548	540	532	524	516	509	501
130	690	681	672	663	654	646	637	628	619	610	602	593	585	576	568	560	552	544	536	529	521	514
135	700	692	683	674	665	656	648	639	630	622	613	605	596	588	580	572	564	556	548	541	533	526
140	710	702	693	684	676	667	658	650	641	632	624	616	607	599	591	583	575	567	560	552	545	538
145	720	712	703	694	686	677	669	660	652	643	635	626	618	610	602	594	586	579	571	563	556	549
150	730	721	713	704	696	687	679	670	662	653	645	637	629	621	613	605	597	589	582	574	567	560
155	739	731	722	714	705	697	688	680	672	663	655	647	639	631	623	615	607	600	592	585	578	570
160	748	740	732	723	715	706	698	690	681	673	665	657	649	641	633	625	618	610	603	595	588	581
165	757	749	741	732	724	716	707	699	691	683	675	667	659	651	643	635	627	620	612	605	598	591
170	766	758	750	741	733	725	717	708	700	692	684	676	668	660	652	645	637	630	622	615	608	601
175	775	766	758	750	742	734	726	718	709	701	693	685	677	670	662	654	647	639	632	624	617	610
180	783	775	767	759	751	743	735	726	718	710	702	694	687	679	671	663	656	648	641	634	627	620
185	791	783	775	767	759	751	743	735	727	719	711	703	696	688	680	672	665	657	650	643	636	629
190	800	792	784	776	768	760	752	744	736	728	720	712	704	697	689	681	674	666	659	652	645	638
195	808	800	792	784	776	768	760	752	744	736	729	721	713	705	698	690	683	675	668	661	653	646
200	816	808	800	792	784	776	769	761	753	745	737	729	721	714	706	699	691	684	676	669	662	655
205	824	816	808	800	792	785	777	769	761	753	745	738	730	722	715	707	700	692	685	678	671	664
210	831	824	816	808	800	793	785	777	769	761	753	746	738	730	723	715	708	701	693	686	679	672
215	839	832	824	816	808	801	793	785	777	769	762	754	746	739	731	723	716	709	701	694	687	680
220	847	839	832	824	816	808	801	793	785	777	769	762	754	747	739	732	724	717	710	702	695	688
230	862	854	847	839	831	824	816	808	800	793	785	777	770	762	755	747	740	733	725	718	711	704
240	876	869	861	854	846	839	831	823	816	808	800	793	785	778	770	763	755	748	741	734	727	720

TABLE 3. - THERMAL CONDUCTIVITY OF NITROGEN

μW/CM SEC °K

T, DEG K	156	158	160	162	164	166	168	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198
P, ATM	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1	145	146	148	150	151	153	155	156	158	160	161	163	165	166	168	170	171	173	175	176	178	179
5	149	151	153	154	156	158	159	161	162	164	166	167	169	170	172	174	175	177	178	180	182	183
10	155	157	159	160	162	163	165	166	168	169	171	172	174	175	177	179	180	182	183	185	186	188
15	162	163	165	166	168	169	170	172	173	175	176	178	179	181	182	184	185	186	188	189	191	192
20	169	170	171	173	174	175	176	178	179	180	182	183	185	186	187	189	190	191	193	194	196	197
25	177	178	179	180	181	182	183	184	185	186	188	189	190	191	193	194	195	197	198	199	201	202
30	185	186	186	187	188	189	190	191	192	193	194	195	196	197	198	200	201	202	203	204	206	207
35	195	195	195	196	196	197	197	198	199	200	201	202	202	203	204	205	207	208	209	210	211	212
40	205	205	205	205	205	205	206	206	206	207	208	208	209	210	211	212	213	213	214	215	216	217
45	217	216	215	215	215	214	214	214	215	215	215	216	216	217	217	218	219	220	220	221	222	223
50	231	229	227	226	225	224	224	223	223	223	223	223	224	224	224	225	225	226	227	227	228	229
55	246	243	240	238	236	235	234	233	233	232	232	232	232	232	232	232	232	233	233	234	234	235
60	263	258	255	251	249	247	245	244	243	242	241	240	240	240	240	240	240	240	240	240	241	241
65	281	275	270	266	262	259	257	255	253	252	250	250	249	248	248	247	247	247	247	247	247	248
70	301	293	287	281	277	273	269	267	264	262	261	259	258	257	256	255	255	255	254	254	254	254
75	322	312	304	297	292	287	283	279	276	273	271	269	267	266	265	264	263	262	262	261	261	261
80	342	331	322	314	307	301	296	292	288	285	282	280	277	276	274	273	271	270	270	269	268	268
85	361	350	340	331	323	316	310	305	301	297	293	290	288	285	283	282	280	279	278	277	276	275
90	380	368	357	347	339	331	324	318	313	309	305	301	298	295	293	291	289	287	286	285	284	283
95	398	385	374	363	354	346	339	332	326	321	316	312	309	306	303	300	298	296	294	293	291	290
100	415	402	390	379	369	360	352	345	339	333	328	324	319	316	313	310	307	305	303	301	299	298
105	431	418	406	394	384	375	366	359	352	345	340	335	330	326	323	319	316	314	311	309	307	306
110	446	433	420	409	398	389	380	372	364	358	352	346	341	337	333	329	326	323	320	318	316	314
115	460	447	435	423	412	402	393	384	377	370	363	357	352	347	343	339	335	332	329	326	324	322
120	474	461	448	436	425	415	406	397	389	381	374	368	363	357	353	348	344	341	338	335	332	329
125	487	474	461	449	438	428	418	409	400	393	386	379	373	368	363	358	354	350	346	343	340	337
130	500	487	474	462	450	440	430	421	412	404	397	390	384	378	372	367	363	359	355	352	348	345
135	512	499	486	474	462	452	442	432	423	415	407	400	394	388	382	377	372	368	364	360	357	353
140	524	510	498	485	474	463	453	443	434	426	418	411	404	398	392	386	381	377	372	368	365	361
145	535	522	509	497	485	474	464	454	445	436	428	421	414	407	401	395	390	385	381	377	373	369
150	546	533	520	508	496	485	474	465	455	447	438	431	423	417	410	405	399	394	389	385	381	377
155	557	543	530	518	506	495	485	475	465	457	448	440	433	426	420	414	408	403	398	393	389	385
160	567	554	541	528	517	506	495	485	475	466	458	450	442	435	429	422	417	411	406	401	397	393
165	577	564	551	539	527	516	505	495	485	476	467	459	451	444	437	431	425	419	414	409	405	400
170	587	573	561	548	537	525	514	504	495	485	477	468	460	453	446	440	433	428	422	417	412	408
175	596	583	570	558	546	535	524	514	504	494	486	477	469	462	455	448	442	436	430	425	420	416
180	606	592	580	567	555	544	533	523	513	503	494	486	478	470	463	456	450	444	438	433	428	423
185	615	602	589	576	565	553	542	532	522	512	503	495	486	479	471	464	458	452	446	440	435	430
190	624	611	598	585	573	562	551	541	530	521	512	503	495	487	480	473	466	460	454	448	443	438
195	633	619	607	594	582	571	560	549	539	529	520	511	503	495	488	480	474	467	461	455	450	445
200	641	628	615	603	591	579	568	558	547	538	528	520	511	503	495	488	481	475	469	463	457	452
205	650	637	624	611	599	588	577	566	556	546	537	528	519	511	503	496	489	482	476	470	464	459
210	658	645	632	620	608	596	585	574	564	554	545	536	527	519	511	503	496	490	483	477	471	466
215	666	653	640	628	616	604	593	582	572	562	552	543	535	526	518	511	504	497	490	484	478	473
220	675	661	648	636	624	612	601	590	580	570	560	551	542	534	526	518	511	504	498	491	485	480
230	690	677	664	652	639	628	616	606	595	585	575	566	557	549	541	533	525	518	511	505	499	493
240	706	692	680	667	655	643	632	621	610	600	590	581	572	563	555	547	539	532	525	518	512	506

TABLE 3. - THERMAL CONDUCTIVITY OF NITROGEN

μJ/CM SEC °K

T, DEG K	200	205	210	215	220	225	230	235	240	245	250	255	260	265	270	275	280	285	290	295	300	305
P, ATM	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1	181	185	189	193	197	201	205	209	213	217	221	225	228	232	236	240	243	247	251	254	258	262
5	185	189	193	197	201	205	208	212	216	220	224	227	231	235	239	242	246	250	253	257	261	264
10	189	193	197	201	205	208	212	216	220	224	227	231	235	238	242	246	249	253	256	260	264	267
15	194	198	201	205	209	212	216	220	223	227	231	234	238	242	245	249	252	256	259	263	266	270
20	198	202	206	209	213	216	220	223	227	231	234	238	241	245	248	252	255	259	262	266	269	273
25	203	207	210	213	217	220	224	227	231	234	238	241	245	248	252	255	258	262	265	269	272	276
30	208	211	215	218	221	224	228	231	234	238	241	245	248	251	255	258	261	265	268	272	275	278
35	213	216	219	222	225	229	232	235	238	241	245	248	251	255	258	261	265	268	271	274	278	281
40	218	221	224	227	230	233	236	239	242	245	248	252	255	258	261	264	268	271	274	277	281	284
45	224	226	229	232	234	237	240	243	246	249	252	255	258	261	264	268	271	274	277	280	283	287
50	230	232	234	236	239	242	244	247	250	253	256	259	262	265	268	271	274	277	280	283	286	289
55	235	237	239	241	244	246	249	251	254	257	259	262	265	268	271	274	277	280	283	286	289	292
60	242	243	245	246	249	251	253	255	258	261	263	266	269	272	274	277	280	283	286	289	292	295
65	248	249	250	252	254	255	258	260	262	265	267	270	272	275	278	281	283	286	289	292	295	298
70	254	255	256	257	259	260	262	264	266	269	271	274	276	279	281	284	287	289	292	295	298	301
75	261	261	262	263	264	265	267	269	271	273	275	277	280	282	285	287	290	293	295	298	301	303
80	268	267	268	268	269	270	272	273	275	277	279	281	283	286	288	291	293	296	298	301	304	306
85	275	274	274	274	274	275	277	278	280	281	283	285	287	289	292	294	296	299	301	304	307	309
90	282	281	280	280	280	281	281	283	284	286	287	289	291	293	295	298	300	302	305	307	310	312
95	289	287	286	286	286	286	286	287	289	290	291	293	295	297	299	301	303	305	308	310	313	315
100	297	294	293	292	291	291	292	292	293	294	296	297	299	301	303	305	307	309	311	313	316	318
105	304	301	299	298	297	297	297	297	298	299	300	301	303	304	306	308	310	312	314	316	319	321
110	312	308	306	304	303	302	302	302	302	303	304	305	307	308	310	312	313	315	317	320	322	324
115	320	315	312	310	309	308	307	307	307	308	309	310	311	312	314	315	317	319	321	323	325	327
120	327	323	319	316	315	313	312	312	312	312	313	314	315	316	317	319	320	322	324	326	328	330
125	335	330	326	323	320	319	318	317	317	317	317	318	319	320	321	322	324	326	327	329	331	333
130	343	337	333	329	326	324	323	322	322	322	322	322	323	324	325	326	327	329	331	332	334	336
135	351	344	339	336	332	330	328	327	327	326	326	326	327	328	329	330	331	332	334	336	337	339
140	358	352	346	342	338	336	334	332	331	331	331	331	331	332	332	333	335	336	337	339	340	342
145	366	359	353	348	345	342	339	338	336	336	335	335	335	336	336	337	338	339	341	342	344	345
150	374	366	360	355	351	347	345	343	341	340	340	339	339	340	340	341	342	343	344	345	347	348
155	381	373	367	361	357	353	350	348	346	345	344	344	344	344	344	345	345	346	347	349	350	351
160	389	380	373	368	363	359	356	353	351	350	349	348	348	348	348	348	349	350	351	352	353	354
165	396	388	380	374	369	365	361	358	356	354	353	352	352	352	352	352	353	353	354	355	356	358
170	404	395	387	380	375	370	367	363	361	359	358	357	356	356	356	356	356	357	357	358	359	361
175	411	402	393	387	381	376	372	369	366	364	362	361	360	360	360	360	360	360	361	362	363	364
180	418	409	400	393	387	382	377	374	371	369	367	365	364	364	363	363	363	364	364	365	366	367
185	426	415	407	399	393	387	383	379	376	373	371	370	369	368	367	367	367	367	368	368	369	370
190	433	422	413	405	399	393	388	384	381	378	376	374	373	372	371	371	371	371	371	372	372	373
195	440	429	420	411	405	399	394	389	386	383	381	379	377	376	375	375	374	374	375	375	375	376
200	447	436	426	418	410	404	399	395	391	388	385	383	381	380	379	378	378	378	378	378	379	379
205	454	442	432	424	416	410	404	400	396	392	390	387	385	384	383	382	382	381	381	382	382	382
210	461	449	439	430	422	415	410	405	401	397	394	392	390	388	387	386	385	385	385	385	385	386
215	468	455	445	436	428	421	415	410	405	402	399	396	394	392	391	390	389	388	388	388	388	389
220	474	462	451	442	434	426	420	415	410	406	403	400	398	396	395	393	393	392	392	392	392	392
230	487	475	463	453	445	437	431	425	420	416	412	409	406	404	402	401	400	399	399	398	398	398
240	500	487	475	465	456	448	441	435	430	425	421	418	415	412	410	409	407	406	405	405	405	404

TABLE 3. - THERMAL CONDUCTIVITY OF NITROGEN

μJ/CM SEC °K

T, DEG K	310	320	330	340	350	360	370	380	390	400	410	420	430	440	450	460	470	480	490	500	510	520
P, ATM	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1	265	272	280	287	294	300	307	314	321	327	334	340	346	353	359	365	371	377	384	390	395	401
5	268	275	282	289	296	303	309	316	323	329	336	342	348	355	361	367	373	379	385	391	397	403
10	271	278	285	291	298	305	312	318	325	331	338	344	350	357	363	369	375	381	387	393	399	405
15	273	280	287	294	301	307	314	321	327	333	340	346	352	359	365	371	377	383	389	395	401	406
20	276	283	290	296	303	310	316	323	329	336	342	348	354	361	367	373	379	385	391	396	402	408
25	279	286	292	299	306	312	319	325	331	338	344	350	356	362	368	374	380	386	392	398	404	410
30	282	288	295	301	308	314	321	327	333	340	346	352	358	364	370	376	382	388	394	400	405	411
35	284	291	297	304	310	317	323	329	336	342	348	354	360	366	372	378	384	390	396	401	407	413
40	287	293	300	306	313	319	325	331	338	344	350	356	362	368	374	380	386	391	397	403	409	414
45	290	296	302	309	315	321	327	334	340	346	352	358	364	370	376	382	387	393	399	405	410	416
50	292	299	305	311	317	323	330	336	342	348	354	360	366	372	377	383	389	395	400	406	412	417
55	295	301	307	314	320	326	332	338	344	350	356	362	368	373	379	385	391	396	402	408	413	419
60	298	304	310	316	322	328	334	340	346	352	358	364	369	375	381	387	392	398	404	409	415	420
65	301	307	312	318	324	330	336	342	348	354	360	365	371	377	383	388	394	400	405	411	416	422
70	303	309	315	321	327	333	338	344	350	356	362	367	373	379	384	390	396	401	407	412	418	423
75	306	312	318	323	329	335	341	346	352	358	364	369	375	381	386	392	397	403	408	414	419	425
80	309	315	320	326	331	337	343	348	354	360	365	371	377	382	388	394	399	405	410	415	421	426
85	312	317	323	328	334	339	345	351	356	362	367	373	379	384	390	395	401	406	412	417	422	428
90	315	320	325	331	336	342	347	353	358	364	369	375	380	386	391	397	402	408	413	419	424	429
95	318	323	328	333	339	344	349	355	360	366	371	377	382	388	393	399	404	409	415	420	425	431
100	320	325	331	336	341	346	352	357	362	368	373	379	384	390	395	400	406	411	416	422	427	432
105	323	328	333	338	343	349	354	359	364	370	375	381	386	391	397	402	407	413	418	423	428	434
110	326	331	336	341	346	351	356	361	367	372	377	382	388	393	398	404	409	414	419	425	430	435
115	329	334	338	343	348	353	358	363	369	374	379	384	390	395	400	405	411	416	421	426	431	437
120	332	336	341	346	351	356	361	366	371	376	381	386	391	397	402	407	412	417	423	428	433	438
125	335	339	344	348	353	358	363	368	373	378	383	388	393	398	404	409	414	419	424	429	434	440
130	338	342	346	351	356	360	365	370	375	380	385	390	395	400	405	410	416	421	426	431	436	441
135	341	345	349	353	358	363	367	372	377	382	387	392	397	402	407	412	417	422	427	432	437	442
140	344	348	352	356	360	365	370	374	379	384	389	394	399	404	409	414	419	424	429	434	439	444
145	347	351	354	359	363	367	372	377	381	386	391	396	401	406	411	416	421	426	430	435	440	445
150	350	353	357	361	365	370	374	379	383	388	393	398	403	407	412	417	422	427	432	437	442	447
155	353	356	360	364	368	372	376	381	385	390	395	400	404	409	414	419	424	429	434	439	443	448
160	356	359	363	366	370	374	379	383	388	392	397	401	406	411	416	421	425	430	435	440	445	450
165	359	362	365	369	373	377	381	385	390	394	399	403	408	413	418	422	427	432	437	442	446	451
170	362	365	368	371	375	379	383	387	392	396	401	405	410	415	419	424	429	434	438	443	448	453
175	365	368	371	374	378	382	386	390	394	398	403	407	412	416	421	426	430	435	440	445	449	454
180	368	371	373	377	380	384	388	392	396	400	405	409	414	418	423	427	432	437	441	446	451	456
185	371	373	376	379	383	386	390	394	398	402	407	411	415	420	425	429	434	438	443	448	452	457
190	374	376	379	382	385	389	392	396	400	404	409	413	417	422	426	431	435	440	445	449	454	459
195	377	379	382	385	388	391	395	398	402	406	411	415	419	424	428	433	437	442	446	451	455	460
200	380	382	384	387	390	393	397	401	405	409	413	417	421	425	430	434	439	443	448	452	457	461
205	383	385	387	390	393	396	399	403	407	411	415	419	423	427	432	436	440	445	449	454	458	463
210	386	388	390	392	395	398	402	405	409	413	417	421	425	429	433	438	442	446	451	455	460	464
215	389	391	393	395	398	401	404	407	411	415	419	423	427	431	435	439	444	448	452	457	461	466
220	392	394	395	398	400	403	406	410	413	417	421	424	428	433	437	441	445	450	454	458	463	467
230	398	399	401	403	405	408	411	414	417	421	425	428	432	436	440	444	449	453	457	461	466	470
240	405	405	406	408	410	413	415	418	422	425	428	432	436	440	444	448	452	456	460	465	469	473

TABLE 3. - THERMAL CONDUCTIVITY OF NITROGEN

µW/CM SEC °K

T, DEG K	530	540	550	560	570	580	590	600	610	620	630	640	650	660	670	680	690	700	710	720	730	740
P, ATM	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
1	407	413	419	424	430	436	441	447	452	457	463	468	473	479	484	489	494	499	504	509	514	519
5	409	414	420	426	431	437	442	448	453	459	464	469	475	480	485	490	495	500	506	511	516	520
10	410	416	422	427	433	439	444	449	455	460	466	471	476	481	487	492	497	502	507	512	517	522
15	412	418	423	429	435	440	446	451	456	462	467	472	478	483	488	493	498	503	508	513	518	523
20	414	419	425	431	436	442	447	452	458	463	468	474	479	484	489	494	499	504	509	514	519	524
25	415	421	426	432	438	443	448	454	459	464	470	475	480	485	490	495	501	506	511	515	520	525
30	417	422	428	433	439	444	450	455	460	466	471	476	481	487	492	497	502	507	512	517	522	526
35	418	424	429	435	440	446	451	457	462	467	472	478	483	488	493	498	503	508	513	518	523	528
40	420	425	431	436	442	447	453	458	463	468	474	479	484	489	494	499	504	509	514	519	524	529
45	421	427	432	438	443	449	454	459	464	470	475	480	485	490	495	500	505	510	515	520	525	530
50	423	428	434	439	445	450	455	461	466	471	476	481	486	491	496	501	506	511	516	521	526	531
55	424	430	435	441	446	451	457	462	467	472	477	482	488	493	498	503	508	512	517	522	527	532
60	426	431	437	442	447	453	458	463	468	473	479	484	489	494	499	504	509	514	518	523	528	533
65	427	433	438	443	449	454	459	464	470	475	480	485	490	495	500	505	510	515	520	524	529	534
70	429	434	439	445	450	455	461	466	471	476	481	486	491	496	501	506	511	516	521	525	530	535
75	430	436	441	446	451	457	462	467	472	477	482	487	492	497	502	507	512	517	522	527	531	536
80	432	437	442	448	453	458	463	468	473	478	484	489	494	498	503	508	513	518	523	528	532	537
85	433	438	444	449	454	459	464	470	475	480	485	490	495	500	505	509	514	519	524	529	533	538
90	435	440	445	450	455	461	466	471	476	481	486	491	496	501	506	511	515	520	525	530	534	539
95	436	441	446	452	457	462	467	472	477	482	487	492	497	502	507	512	516	521	526	531	535	540
100	437	443	448	453	458	463	468	473	478	483	488	493	498	503	508	513	518	522	527	532	536	541
105	439	444	449	454	459	465	470	475	480	485	490	494	499	504	509	514	519	523	528	533	538	542
110	440	445	451	456	461	466	471	476	481	486	491	496	500	505	510	515	520	524	529	534	539	543
115	442	447	452	457	462	467	472	477	482	487	492	497	502	506	511	516	521	526	530	535	540	544
120	443	448	453	458	463	468	473	478	483	488	493	498	503	508	512	517	522	527	531	536	541	545
125	445	450	455	460	465	470	475	480	485	489	494	499	504	509	514	518	523	528	532	537	542	546
130	446	451	456	461	466	471	476	481	486	491	495	500	505	510	515	519	524	529	533	538	543	547
135	447	452	457	462	467	472	477	482	487	492	497	501	506	511	516	520	525	530	534	539	544	548
140	449	454	459	464	469	474	479	483	488	493	498	503	507	512	517	522	526	531	535	540	545	549
145	450	455	460	465	470	475	480	485	489	494	499	504	509	513	518	523	527	532	537	541	546	550
150	452	457	462	466	471	476	481	486	491	495	500	505	510	514	519	524	528	533	538	542	547	551
155	453	458	463	468	473	477	482	487	492	497	501	506	511	515	520	525	529	534	539	543	548	552
160	455	459	464	469	474	479	484	488	493	498	503	507	512	517	521	526	530	535	540	544	549	553
165	456	461	466	471	475	480	485	490	494	499	504	508	513	518	522	527	532	536	541	545	550	554
170	458	462	467	472	477	481	486	491	496	500	505	510	514	519	523	528	533	537	542	546	551	555
175	459	464	468	473	478	483	487	492	497	501	506	511	515	520	525	529	534	538	543	547	552	556
180	460	465	470	475	479	484	489	493	498	503	507	512	516	521	526	530	535	539	544	548	553	557
185	462	466	471	476	481	485	490	495	499	504	508	513	518	522	527	531	536	540	545	549	554	558
190	463	468	473	477	482	486	491	496	500	505	510	514	519	523	528	532	537	541	546	550	555	559
195	465	469	474	479	483	488	492	497	502	506	511	515	520	524	529	533	538	542	547	551	556	560
200	466	471	475	480	484	489	494	498	503	507	512	516	521	525	530	534	539	543	548	552	557	561
205	467	472	477	481	486	490	495	499	504	509	513	518	522	527	531	536	540	544	549	553	558	562
210	469	473	478	483	487	492	496	501	505	510	514	519	523	528	532	537	541	545	550	554	559	563
215	470	475	479	484	488	493	497	502	506	511	515	520	524	529	533	538	542	546	551	555	560	564
220	472	476	481	485	490	494	499	503	508	512	517	521	525	530	534	539	543	547	552	556	561	565
230	475	479	483	488	492	497	501	506	510	514	519	523	528	532	536	541	545	550	554	558	563	567
240	477	482	486	490	495	499	504	508	512	517	521	526	530	534	539	543	547	552	556	560	564	569

The variation of the isobaric specific heat, $C_P = \left(\frac{\partial H}{\partial T}\right)_P$, is a function of the second derivative of the PVT surface, and a common fault of closed equations of state is to yield C_P values not in good agreement with experimental results. Isobaric specific heat values (39) derived from the equation of state of Wood and coworkers (41) are within 2 percent of like quantities obtained from flow calorimetry. However, experimental data above 136 atmospheres are lacking, and the accuracy of C_P values computed for higher pressures are not well substantiated. The equation of state (41), a virial power series in density truncated at the fifth virial coefficient, was not designed for pressures above 300 atmospheres or temperatures below 133.15° K. Failure of this equation of state to generate the PVT surface for nitrogen is apparent for temperatures only a few degrees below 133° K.

A common characteristic of gases in the vicinity of the critical temperature is that at pressures above the critical pressure the isobaric heat capacity versus temperature curve rises rapidly to a maximum and then decreases, the maximum becoming less sharp as the pressure increases. The C_P values derived from the equation of state conform to this generalization and illustrate the ability of the equation of state to predict the appropriate behavior of the real gas. Unfortunately, the accuracy of the C_P values computed cannot be substantiated at all conditions applied in obtaining the Prandtl numbers of nitrogen because of the lack of suitable experimental data. Tabular values of the Prandtl numbers of nitrogen are presented in table 4.

TABLE 4 - 5 pages, pg. #s 34, 35, 36, 37, 38,

TABLE 4. - PRANDTL NUMBERS OF NITROGEN

T, DEG K	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147
P, ATM	PRANDTL NUMBERS														
1	0.765	0.765	0.765	0.764	0.764	0.763	0.763	0.763	0.762	0.762	0.762	0.761	0.761	0.761	0.760
5	0.784	0.783	0.782	0.781	0.780	0.779	0.778	0.778	0.777	0.776	0.775	0.774	0.774	0.773	0.772
10	0.821	0.819	0.817	0.815	0.813	0.811	0.809	0.807	0.805	0.803	0.802	0.800	0.799	0.797	0.796
15	0.877	0.873	0.868	0.864	0.860	0.856	0.852	0.849	0.845	0.842	0.839	0.836	0.833	0.830	0.828
20	0.962	0.952	0.943	0.935	0.927	0.920	0.913	0.906	0.900	0.894	0.889	0.884	0.879	0.874	0.870
25	1.098	1.077	1.059	1.042	1.027	1.013	1.000	0.988	0.977	0.967	0.958	0.949	0.941	0.933	0.925
30	1.346	1.296	1.254	1.217	1.185	1.157	1.132	1.109	1.089	1.071	1.054	1.038	1.024	1.011	0.999
35	1.930	1.763	1.638	1.541	1.463	1.399	1.344	1.298	1.258	1.223	1.193	1.165	1.141	1.119	1.099
40	4.469	3.257	2.648	2.281	2.035	1.857	1.723	1.617	1.532	1.461	1.402	1.351	1.307	1.268	1.235
45	4.909	5.469	5.046	4.100	3.331	2.805	2.443	2.184	1.991	1.841	1.723	1.626	1.546	1.479	1.421
50	3.121	3.406	3.699	3.914	3.927	3.699	3.336	2.965	2.645	2.385	2.177	2.009	1.873	1.761	1.667
55	2.524	2.660	2.807	2.957	3.091	3.182	3.200	3.129	2.982	2.791	2.589	2.397	2.226	2.077	1.948
60	2.220	2.301	2.387	2.477	2.565	2.647	2.713	2.752	2.756	2.719	2.644	2.540	2.420	2.294	2.171
65	2.033	2.088	2.145	2.203	2.262	2.320	2.372	2.417	2.449	2.464	2.459	2.431	2.384	2.319	2.241
70	1.904	1.944	1.985	2.027	2.069	2.110	2.149	2.185	2.215	2.239	2.252	2.254	2.244	2.221	2.185
75	1.809	1.841	1.872	1.904	1.935	1.966	1.995	2.023	2.048	2.069	2.085	2.095	2.099	2.094	2.081
80	1.737	1.762	1.787	1.812	1.836	1.860	1.883	1.905	1.925	1.942	1.957	1.968	1.975	1.978	1.975
85	1.678	1.699	1.720	1.740	1.760	1.779	1.798	1.815	1.831	1.846	1.858	1.868	1.876	1.880	1.881
90	1.631	1.649	1.666	1.683	1.700	1.715	1.730	1.745	1.758	1.770	1.780	1.789	1.796	1.801	1.803
95	1.591	1.607	1.622	1.636	1.650	1.664	1.676	1.688	1.699	1.709	1.717	1.725	1.731	1.735	1.738
100	1.557	1.571	1.584	1.597	1.609	1.621	1.631	1.641	1.650	1.659	1.666	1.672	1.677	1.681	1.684
105	1.528	1.541	1.552	1.564	1.574	1.584	1.593	1.602	1.610	1.617	1.623	1.628	1.633	1.636	1.638
110	1.503	1.514	1.525	1.535	1.544	1.553	1.561	1.569	1.575	1.581	1.587	1.591	1.595	1.598	1.600
115	1.480	1.491	1.501	1.510	1.518	1.526	1.534	1.540	1.546	1.551	1.556	1.559	1.562	1.565	1.566
120	1.460	1.470	1.479	1.488	1.496	1.503	1.509	1.515	1.520	1.525	1.529	1.532	1.535	1.536	1.538
125	1.442	1.452	1.460	1.468	1.476	1.482	1.488	1.493	1.498	1.502	1.505	1.508	1.510	1.512	1.513
130	1.426	1.435	1.443	1.451	1.458	1.464	1.469	1.474	1.478	1.482	1.484	1.487	1.489	1.490	1.491
135	1.412	1.420	1.428	1.435	1.441	1.447	1.452	1.457	1.460	1.463	1.466	1.468	1.470	1.471	1.471
140	1.399	1.407	1.414	1.421	1.427	1.432	1.437	1.441	1.444	1.447	1.450	1.451	1.453	1.453	1.454
145	1.387	1.394	1.402	1.408	1.414	1.419	1.423	1.427	1.430	1.433	1.435	1.436	1.438	1.438	1.438
150	1.375	1.383	1.390	1.396	1.402	1.407	1.411	1.414	1.417	1.420	1.422	1.423	1.424	1.424	1.424
155	1.365	1.373	1.379	1.385	1.391	1.395	1.399	1.403	1.406	1.408	1.410	1.411	1.411	1.412	1.412
160	1.356	1.363	1.370	1.376	1.381	1.385	1.389	1.392	1.395	1.397	1.399	1.400	1.400	1.400	1.400
165	1.347	1.354	1.361	1.366	1.371	1.376	1.379	1.383	1.385	1.387	1.388	1.389	1.390	1.390	1.390
170	1.339	1.346	1.352	1.358	1.363	1.367	1.371	1.374	1.376	1.378	1.379	1.380	1.381	1.381	1.380
175	1.331	1.338	1.344	1.350	1.355	1.359	1.362	1.365	1.368	1.370	1.371	1.372	1.372	1.372	1.371
180	1.324	1.331	1.337	1.343	1.347	1.351	1.355	1.358	1.360	1.362	1.363	1.364	1.364	1.364	1.363
185	1.317	1.324	1.330	1.336	1.341	1.345	1.348	1.351	1.353	1.355	1.356	1.356	1.357	1.357	1.356
190	1.311	1.318	1.324	1.329	1.334	1.338	1.341	1.344	1.346	1.348	1.349	1.350	1.350	1.350	1.349
195	1.305	1.312	1.318	1.323	1.328	1.332	1.335	1.338	1.340	1.342	1.343	1.344	1.344	1.344	1.343
200	1.299	1.306	1.312	1.318	1.322	1.326	1.330	1.332	1.334	1.336	1.337	1.338	1.338	1.338	1.337
205	1.294	1.301	1.307	1.313	1.317	1.321	1.324	1.327	1.329	1.331	1.332	1.332	1.332	1.332	1.332
210	1.289	1.296	1.302	1.308	1.312	1.316	1.319	1.322	1.324	1.326	1.327	1.327	1.327	1.327	1.327
215	1.284	1.291	1.297	1.303	1.307	1.311	1.315	1.317	1.319	1.321	1.322	1.323	1.323	1.322	1.322
220	1.280	1.287	1.293	1.298	1.303	1.307	1.310	1.313	1.315	1.316	1.318	1.318	1.318	1.318	1.317
225	1.276	1.283	1.289	1.294	1.299	1.303	1.306	1.309	1.311	1.312	1.313	1.314	1.314	1.314	1.313
230	1.272	1.279	1.285	1.290	1.295	1.299	1.302	1.305	1.307	1.308	1.309	1.310	1.310	1.310	1.310
235	1.268	1.275	1.281	1.286	1.291	1.295	1.298	1.301	1.303	1.305	1.306	1.306	1.307	1.306	1.306
240	1.264	1.271	1.277	1.283	1.287	1.291	1.295	1.297	1.300	1.301	1.302	1.303	1.303	1.303	1.303

TABLE 4. - PRANDTL NUMBERS OF NITROGEN

T, DEG K	148	150	152	154	156	158	160	162	164	166	168	170	172	174	176
P, ATM							PRANDTL NUMBERS								
1	0.760	0.759	0.758	0.758	0.757	0.756	0.756	0.755	0.754	0.754	0.753	0.753	0.752	0.751	0.751
5	0.771	0.770	0.769	0.767	0.766	0.765	0.764	0.763	0.762	0.761	0.760	0.759	0.758	0.757	0.756
10	0.794	0.792	0.789	0.786	0.784	0.782	0.780	0.778	0.776	0.774	0.772	0.771	0.769	0.768	0.766
15	0.825	0.820	0.816	0.812	0.808	0.804	0.801	0.798	0.795	0.792	0.789	0.787	0.784	0.782	0.780
20	0.866	0.858	0.851	0.844	0.838	0.832	0.827	0.822	0.818	0.813	0.809	0.806	0.802	0.799	0.796
25	0.919	0.906	0.895	0.884	0.875	0.867	0.859	0.852	0.845	0.839	0.833	0.828	0.823	0.819	0.815
30	0.988	0.968	0.950	0.935	0.921	0.908	0.897	0.887	0.878	0.869	0.861	0.854	0.848	0.842	0.836
35	1.080	1.048	1.021	0.997	0.977	0.959	0.943	0.929	0.916	0.904	0.894	0.884	0.875	0.867	0.860
40	1.204	1.153	1.111	1.076	1.046	1.020	0.997	0.978	0.960	0.945	0.931	0.918	0.907	0.896	0.887
45	1.371	1.289	1.224	1.172	1.129	1.092	1.061	1.035	1.011	0.991	0.972	0.956	0.941	0.928	0.916
50	1.588	1.461	1.365	1.289	1.228	1.177	1.135	1.100	1.069	1.042	1.019	0.998	0.980	0.963	0.948
55	1.838	1.661	1.527	1.423	1.340	1.273	1.218	1.172	1.133	1.099	1.069	1.044	1.021	1.001	0.983
60	2.055	1.853	1.692	1.563	1.459	1.376	1.307	1.249	1.201	1.159	1.123	1.092	1.065	1.040	1.019
65	2.157	1.985	1.825	1.688	1.572	1.475	1.395	1.327	1.270	1.221	1.178	1.142	1.109	1.081	1.056
70	2.139	2.025	1.898	1.774	1.660	1.560	1.474	1.399	1.335	1.280	1.232	1.191	1.154	1.122	1.093
75	2.060	1.995	1.909	1.812	1.714	1.621	1.536	1.460	1.393	1.334	1.282	1.237	1.197	1.161	1.130
80	1.966	1.932	1.878	1.809	1.733	1.654	1.577	1.505	1.439	1.379	1.326	1.278	1.236	1.198	1.164
85	1.879	1.861	1.828	1.781	1.724	1.661	1.596	1.532	1.471	1.413	1.361	1.313	1.269	1.230	1.194
90	1.803	1.794	1.774	1.742	1.700	1.651	1.598	1.543	1.489	1.436	1.386	1.339	1.296	1.257	1.221
95	1.739	1.735	1.721	1.699	1.668	1.631	1.588	1.542	1.495	1.448	1.402	1.358	1.317	1.278	1.243
100	1.685	1.683	1.673	1.657	1.634	1.605	1.571	1.533	1.493	1.451	1.410	1.370	1.331	1.294	1.260
105	1.639	1.638	1.631	1.619	1.601	1.578	1.550	1.518	1.484	1.448	1.412	1.375	1.340	1.305	1.272
110	1.601	1.599	1.594	1.584	1.569	1.551	1.528	1.501	1.472	1.441	1.409	1.376	1.344	1.312	1.280
115	1.567	1.566	1.561	1.553	1.541	1.525	1.505	1.483	1.458	1.431	1.403	1.373	1.344	1.314	1.285
120	1.538	1.537	1.533	1.525	1.515	1.501	1.484	1.465	1.443	1.419	1.394	1.368	1.341	1.314	1.287
125	1.513	1.511	1.507	1.501	1.491	1.479	1.464	1.447	1.428	1.407	1.384	1.361	1.336	1.312	1.287
130	1.491	1.489	1.485	1.479	1.470	1.459	1.446	1.430	1.413	1.394	1.374	1.352	1.330	1.308	1.285
135	1.471	1.469	1.465	1.459	1.451	1.441	1.429	1.415	1.399	1.382	1.363	1.344	1.323	1.303	1.281
140	1.453	1.451	1.447	1.442	1.434	1.424	1.413	1.400	1.386	1.370	1.353	1.335	1.316	1.297	1.277
145	1.438	1.436	1.432	1.426	1.418	1.409	1.399	1.387	1.373	1.359	1.343	1.326	1.309	1.291	1.272
150	1.424	1.421	1.417	1.412	1.404	1.396	1.386	1.374	1.362	1.348	1.333	1.318	1.301	1.285	1.267
155	1.411	1.408	1.404	1.399	1.392	1.383	1.374	1.363	1.351	1.338	1.324	1.310	1.294	1.278	1.262
160	1.399	1.397	1.393	1.387	1.380	1.372	1.363	1.353	1.341	1.329	1.316	1.302	1.287	1.272	1.257
165	1.389	1.386	1.382	1.377	1.370	1.362	1.353	1.343	1.332	1.320	1.308	1.294	1.281	1.266	1.252
170	1.379	1.377	1.372	1.367	1.360	1.353	1.344	1.334	1.323	1.312	1.300	1.287	1.274	1.261	1.246
175	1.371	1.368	1.364	1.358	1.352	1.344	1.335	1.326	1.316	1.305	1.293	1.281	1.268	1.255	1.242
180	1.363	1.360	1.355	1.350	1.344	1.336	1.328	1.318	1.308	1.298	1.287	1.275	1.262	1.250	1.237
185	1.355	1.352	1.348	1.343	1.336	1.329	1.321	1.311	1.302	1.291	1.280	1.269	1.257	1.245	1.232
190	1.348	1.345	1.341	1.336	1.329	1.322	1.314	1.305	1.296	1.285	1.275	1.264	1.252	1.240	1.228
195	1.342	1.339	1.335	1.329	1.323	1.316	1.308	1.299	1.290	1.280	1.269	1.259	1.247	1.236	1.224
200	1.336	1.333	1.329	1.324	1.317	1.310	1.302	1.294	1.285	1.275	1.265	1.254	1.243	1.232	1.220
205	1.331	1.328	1.323	1.318	1.312	1.305	1.297	1.289	1.280	1.270	1.260	1.250	1.239	1.228	1.217
210	1.326	1.323	1.318	1.313	1.307	1.300	1.292	1.284	1.275	1.266	1.256	1.246	1.235	1.224	1.213
215	1.321	1.318	1.314	1.309	1.302	1.296	1.288	1.280	1.271	1.262	1.252	1.242	1.232	1.221	1.210
220	1.316	1.314	1.309	1.304	1.298	1.291	1.284	1.276	1.267	1.258	1.248	1.238	1.228	1.218	1.207
225	1.312	1.309	1.305	1.300	1.294	1.288	1.280	1.272	1.263	1.254	1.245	1.235	1.225	1.215	1.204
230	1.309	1.306	1.302	1.297	1.291	1.284	1.276	1.268	1.260	1.251	1.242	1.232	1.222	1.212	1.202
235	1.305	1.302	1.298	1.293	1.287	1.281	1.273	1.265	1.257	1.248	1.239	1.229	1.220	1.210	1.199
240	1.302	1.299	1.295	1.290	1.284	1.277	1.270	1.262	1.254	1.245	1.236	1.227	1.217	1.207	1.197

TABLE 4. - PRANDTL NUMBERS OF NITROGEN

T, DEG K	180	184	188	192	196	200	204	208	212	216	220	224	228	232	236
P, ATM	PRANDTL NUMBERS														
1	0.749	0.748	0.747	0.746	0.745	0.744	0.743	0.742	0.740	0.739	0.738	0.737	0.736	0.735	0.734
5	0.754	0.752	0.751	0.749	0.748	0.746	0.745	0.743	0.742	0.741	0.740	0.738	0.737	0.736	0.735
10	0.763	0.761	0.758	0.756	0.754	0.752	0.750	0.748	0.747	0.745	0.743	0.742	0.740	0.739	0.738
15	0.776	0.772	0.768	0.765	0.762	0.760	0.757	0.755	0.752	0.750	0.748	0.746	0.744	0.743	0.741
20	0.790	0.785	0.780	0.776	0.772	0.768	0.765	0.762	0.759	0.756	0.754	0.752	0.749	0.747	0.745
25	0.807	0.800	0.794	0.788	0.783	0.778	0.774	0.770	0.767	0.763	0.760	0.758	0.755	0.752	0.750
30	0.826	0.817	0.809	0.802	0.795	0.789	0.784	0.779	0.775	0.771	0.767	0.764	0.761	0.758	0.755
35	0.847	0.835	0.825	0.816	0.808	0.801	0.795	0.789	0.784	0.779	0.775	0.771	0.767	0.764	0.761
40	0.870	0.855	0.843	0.832	0.823	0.814	0.807	0.800	0.794	0.788	0.783	0.778	0.774	0.770	0.766
45	0.895	0.877	0.862	0.849	0.838	0.828	0.819	0.811	0.804	0.797	0.791	0.786	0.781	0.776	0.772
50	0.923	0.901	0.883	0.867	0.854	0.842	0.832	0.822	0.814	0.807	0.800	0.794	0.788	0.783	0.778
55	0.952	0.926	0.905	0.886	0.871	0.857	0.845	0.834	0.825	0.816	0.809	0.802	0.796	0.790	0.785
60	0.982	0.952	0.927	0.906	0.888	0.872	0.859	0.847	0.836	0.826	0.818	0.810	0.803	0.797	0.791
65	1.013	0.979	0.950	0.926	0.905	0.888	0.872	0.859	0.847	0.837	0.827	0.819	0.811	0.804	0.798
70	1.045	1.006	0.973	0.946	0.923	0.904	0.887	0.872	0.859	0.847	0.837	0.827	0.819	0.811	0.804
75	1.076	1.032	0.996	0.967	0.941	0.919	0.901	0.884	0.870	0.857	0.846	0.836	0.827	0.818	0.811
80	1.106	1.058	1.019	0.986	0.959	0.935	0.915	0.897	0.881	0.868	0.855	0.844	0.835	0.826	0.818
85	1.133	1.083	1.041	1.006	0.976	0.950	0.928	0.909	0.892	0.878	0.865	0.853	0.842	0.833	0.824
90	1.158	1.105	1.061	1.024	0.992	0.965	0.942	0.921	0.903	0.888	0.874	0.861	0.850	0.840	0.831
95	1.179	1.125	1.080	1.041	1.008	0.979	0.954	0.933	0.914	0.897	0.882	0.869	0.857	0.847	0.837
100	1.197	1.143	1.096	1.056	1.022	0.992	0.967	0.944	0.924	0.907	0.891	0.877	0.865	0.853	0.843
105	1.211	1.158	1.111	1.070	1.035	1.005	0.978	0.954	0.934	0.916	0.899	0.885	0.872	0.860	0.849
110	1.222	1.170	1.123	1.083	1.047	1.016	0.988	0.964	0.943	0.924	0.907	0.892	0.879	0.866	0.855
115	1.230	1.179	1.134	1.093	1.058	1.026	0.998	0.974	0.952	0.932	0.915	0.899	0.885	0.872	0.861
120	1.235	1.187	1.142	1.103	1.067	1.035	1.007	0.982	0.960	0.940	0.922	0.906	0.891	0.878	0.866
125	1.238	1.192	1.149	1.110	1.075	1.043	1.015	0.990	0.967	0.947	0.929	0.912	0.897	0.884	0.872
130	1.239	1.195	1.154	1.116	1.082	1.050	1.022	0.997	0.974	0.953	0.935	0.918	0.903	0.889	0.877
135	1.239	1.197	1.158	1.121	1.087	1.056	1.028	1.003	0.980	0.959	0.940	0.924	0.908	0.894	0.881
140	1.237	1.198	1.160	1.125	1.092	1.061	1.034	1.008	0.985	0.965	0.946	0.929	0.913	0.899	0.886
145	1.235	1.198	1.162	1.127	1.095	1.066	1.038	1.013	0.990	0.970	0.951	0.933	0.918	0.903	0.890
150	1.232	1.197	1.162	1.129	1.098	1.069	1.042	1.018	0.995	0.974	0.955	0.938	0.922	0.908	0.894
155	1.229	1.195	1.162	1.131	1.100	1.072	1.046	1.021	0.999	0.978	0.959	0.942	0.926	0.911	0.898
160	1.225	1.193	1.162	1.131	1.102	1.074	1.049	1.025	1.002	0.982	0.963	0.946	0.930	0.915	0.902
165	1.221	1.191	1.161	1.131	1.103	1.076	1.051	1.027	1.005	0.985	0.966	0.949	0.933	0.918	0.905
170	1.218	1.188	1.159	1.131	1.104	1.077	1.053	1.030	1.008	0.988	0.969	0.952	0.936	0.921	0.908
175	1.214	1.186	1.158	1.130	1.104	1.078	1.054	1.032	1.010	0.990	0.972	0.955	0.939	0.924	0.911
180	1.210	1.183	1.156	1.130	1.104	1.079	1.055	1.033	1.012	0.993	0.974	0.957	0.942	0.927	0.913
185	1.207	1.181	1.154	1.129	1.104	1.079	1.056	1.035	1.014	0.995	0.977	0.960	0.944	0.929	0.916
190	1.203	1.178	1.153	1.128	1.103	1.080	1.057	1.036	1.015	0.996	0.979	0.962	0.946	0.932	0.918
195	1.200	1.175	1.151	1.126	1.103	1.080	1.058	1.037	1.017	0.998	0.980	0.964	0.948	0.934	0.920
200	1.197	1.173	1.149	1.125	1.102	1.080	1.059	1.037	1.018	0.999	0.982	0.965	0.950	0.936	0.922
205	1.194	1.170	1.147	1.124	1.101	1.079	1.058	1.038	1.019	1.000	0.983	0.967	0.952	0.937	0.924
210	1.191	1.168	1.145	1.123	1.100	1.079	1.058	1.038	1.019	1.001	0.984	0.968	0.953	0.939	0.926
215	1.188	1.166	1.143	1.121	1.100	1.079	1.058	1.039	1.020	1.002	0.985	0.970	0.955	0.940	0.927
220	1.186	1.164	1.142	1.120	1.099	1.078	1.058	1.039	1.021	1.003	0.986	0.971	0.956	0.942	0.929
225	1.183	1.162	1.140	1.119	1.098	1.078	1.058	1.039	1.021	1.004	0.987	0.972	0.957	0.943	0.930
230	1.181	1.160	1.139	1.118	1.097	1.077	1.058	1.039	1.021	1.004	0.988	0.973	0.958	0.944	0.931
235	1.179	1.158	1.137	1.117	1.096	1.077	1.058	1.039	1.022	1.005	0.989	0.973	0.959	0.945	0.932
240	1.177	1.156	1.136	1.116	1.096	1.076	1.057	1.039	1.022	1.005	0.989	0.974	0.960	0.946	0.934

TABLE 4. - PRANDTL NUMBERS OF NITROGEN

T, DEG K	240	250	260	270	280	290	300	310	320	330	340	350	360	370	380
P, ATM							PRANDTL NUMBERS								
1	0.733	0.731	0.729	0.727	0.725	0.723	0.721	0.719	0.717	0.715	0.714	0.712	0.711	0.710	0.708
5	0.734	0.731	0.729	0.727	0.724	0.722	0.720	0.718	0.716	0.715	0.713	0.712	0.710	0.709	0.707
10	0.736	0.733	0.730	0.728	0.725	0.723	0.721	0.719	0.717	0.715	0.713	0.711	0.710	0.708	0.707
15	0.740	0.736	0.732	0.729	0.727	0.724	0.722	0.719	0.717	0.715	0.713	0.712	0.710	0.709	0.707
20	0.743	0.739	0.735	0.732	0.728	0.726	0.723	0.720	0.718	0.716	0.714	0.712	0.710	0.709	0.707
25	0.748	0.743	0.738	0.734	0.731	0.727	0.724	0.722	0.719	0.717	0.715	0.713	0.711	0.709	0.708
30	0.752	0.747	0.742	0.737	0.733	0.729	0.726	0.723	0.720	0.718	0.716	0.714	0.712	0.710	0.708
35	0.758	0.751	0.745	0.740	0.736	0.732	0.728	0.725	0.722	0.719	0.717	0.714	0.712	0.710	0.709
40	0.763	0.755	0.749	0.743	0.738	0.734	0.730	0.726	0.723	0.720	0.718	0.715	0.713	0.711	0.709
45	0.768	0.760	0.753	0.746	0.741	0.736	0.732	0.728	0.725	0.722	0.719	0.716	0.714	0.712	0.710
50	0.774	0.765	0.757	0.750	0.744	0.739	0.734	0.730	0.726	0.723	0.720	0.717	0.715	0.713	0.711
55	0.780	0.769	0.761	0.753	0.747	0.741	0.736	0.732	0.728	0.725	0.721	0.719	0.716	0.714	0.712
60	0.786	0.774	0.765	0.757	0.750	0.744	0.738	0.734	0.730	0.726	0.723	0.720	0.717	0.715	0.712
65	0.792	0.779	0.769	0.760	0.753	0.746	0.741	0.736	0.731	0.728	0.724	0.721	0.718	0.715	0.713
70	0.798	0.784	0.773	0.764	0.756	0.749	0.743	0.738	0.733	0.729	0.725	0.722	0.719	0.716	0.714
75	0.804	0.789	0.777	0.767	0.759	0.752	0.745	0.740	0.735	0.731	0.727	0.723	0.720	0.717	0.715
80	0.810	0.795	0.782	0.771	0.762	0.754	0.748	0.742	0.737	0.732	0.728	0.724	0.721	0.718	0.716
85	0.816	0.800	0.786	0.775	0.765	0.757	0.750	0.744	0.738	0.734	0.729	0.726	0.722	0.719	0.716
90	0.822	0.805	0.790	0.778	0.768	0.759	0.752	0.746	0.740	0.735	0.731	0.727	0.723	0.720	0.717
95	0.828	0.809	0.794	0.782	0.771	0.762	0.754	0.748	0.742	0.737	0.732	0.728	0.724	0.721	0.718
100	0.834	0.814	0.798	0.785	0.774	0.765	0.757	0.750	0.744	0.738	0.733	0.729	0.725	0.722	0.719
105	0.840	0.819	0.802	0.789	0.777	0.767	0.759	0.752	0.745	0.740	0.735	0.730	0.727	0.723	0.720
110	0.845	0.824	0.806	0.792	0.780	0.770	0.761	0.754	0.747	0.741	0.736	0.732	0.728	0.724	0.721
115	0.851	0.828	0.810	0.795	0.783	0.772	0.763	0.755	0.749	0.743	0.738	0.733	0.729	0.725	0.722
120	0.856	0.833	0.814	0.798	0.786	0.775	0.765	0.757	0.750	0.744	0.739	0.734	0.730	0.726	0.723
125	0.861	0.837	0.817	0.802	0.788	0.777	0.768	0.759	0.752	0.746	0.740	0.735	0.731	0.727	0.723
130	0.865	0.841	0.821	0.805	0.791	0.779	0.770	0.761	0.754	0.747	0.741	0.736	0.732	0.728	0.724
135	0.870	0.845	0.824	0.808	0.794	0.782	0.772	0.763	0.755	0.749	0.743	0.738	0.733	0.729	0.725
140	0.874	0.849	0.828	0.811	0.796	0.784	0.774	0.765	0.757	0.750	0.744	0.739	0.734	0.730	0.726
145	0.878	0.852	0.831	0.813	0.799	0.786	0.776	0.766	0.758	0.751	0.745	0.740	0.735	0.731	0.727
150	0.882	0.856	0.834	0.816	0.801	0.788	0.777	0.768	0.760	0.753	0.746	0.741	0.736	0.731	0.728
155	0.886	0.859	0.837	0.819	0.803	0.790	0.779	0.770	0.761	0.754	0.748	0.742	0.737	0.732	0.728
160	0.889	0.862	0.840	0.821	0.806	0.792	0.781	0.771	0.763	0.755	0.749	0.743	0.738	0.733	0.729
165	0.892	0.865	0.842	0.824	0.808	0.794	0.783	0.773	0.764	0.757	0.750	0.744	0.739	0.734	0.730
170	0.895	0.868	0.845	0.826	0.810	0.796	0.785	0.774	0.766	0.758	0.751	0.745	0.740	0.735	0.731
175	0.898	0.870	0.847	0.828	0.812	0.798	0.786	0.776	0.767	0.759	0.752	0.746	0.741	0.736	0.731
180	0.901	0.873	0.850	0.830	0.814	0.800	0.788	0.777	0.768	0.760	0.753	0.747	0.742	0.737	0.732
185	0.903	0.875	0.852	0.832	0.816	0.802	0.789	0.779	0.770	0.761	0.754	0.748	0.742	0.737	0.733
190	0.906	0.878	0.854	0.834	0.818	0.803	0.791	0.780	0.771	0.763	0.755	0.749	0.743	0.738	0.734
195	0.908	0.880	0.856	0.836	0.819	0.805	0.792	0.782	0.772	0.764	0.756	0.750	0.744	0.739	0.734
200	0.910	0.882	0.858	0.838	0.821	0.806	0.794	0.783	0.773	0.765	0.757	0.751	0.745	0.740	0.735
205	0.911	0.884	0.860	0.840	0.823	0.808	0.795	0.784	0.774	0.766	0.758	0.752	0.746	0.741	0.736
210	0.913	0.885	0.862	0.842	0.824	0.809	0.797	0.785	0.776	0.767	0.759	0.753	0.747	0.741	0.737
215	0.915	0.887	0.863	0.843	0.826	0.811	0.798	0.787	0.777	0.768	0.760	0.754	0.747	0.742	0.737
220	0.916	0.889	0.865	0.845	0.827	0.812	0.799	0.788	0.778	0.769	0.761	0.754	0.748	0.743	0.738
225	0.918	0.890	0.866	0.846	0.829	0.813	0.800	0.789	0.779	0.770	0.762	0.755	0.749	0.744	0.739
230	0.919	0.892	0.868	0.847	0.830	0.815	0.802	0.790	0.780	0.771	0.763	0.756	0.750	0.744	0.739
235	0.920	0.893	0.869	0.849	0.831	0.816	0.803	0.791	0.781	0.772	0.764	0.757	0.751	0.745	0.740
240	0.921	0.894	0.871	0.850	0.832	0.817	0.804	0.792	0.782	0.773	0.765	0.758	0.751	0.746	0.740

TABLE 4. - PRANDTL NUMBERS OF NITROGEN

T, DEG K	390	415	440	465	490	515	540	565	590	615	640	665	690	715	740
P, ATM							PRANDTL NUMBERS								
1	0.707	0.705	0.702	0.701	0.700	0.699	0.699	0.699	0.700	0.701	0.702	0.704	0.705	0.707	0.709
5	0.706	0.704	0.702	0.700	0.699	0.699	0.698	0.699	0.699	0.700	0.702	0.703	0.705	0.707	0.709
10	0.706	0.703	0.701	0.700	0.699	0.698	0.698	0.698	0.699	0.700	0.701	0.703	0.704	0.706	0.708
15	0.706	0.703	0.701	0.699	0.698	0.698	0.697	0.698	0.698	0.699	0.701	0.702	0.704	0.706	0.708
20	0.706	0.703	0.701	0.699	0.698	0.697	0.697	0.698	0.698	0.699	0.700	0.702	0.704	0.705	0.707
25	0.706	0.703	0.701	0.699	0.698	0.697	0.697	0.697	0.698	0.699	0.700	0.702	0.703	0.705	0.707
30	0.707	0.703	0.701	0.699	0.698	0.697	0.697	0.697	0.698	0.699	0.700	0.701	0.703	0.705	0.707
35	0.707	0.704	0.701	0.699	0.698	0.697	0.697	0.697	0.698	0.699	0.700	0.701	0.703	0.705	0.707
40	0.708	0.704	0.701	0.699	0.698	0.697	0.697	0.697	0.698	0.698	0.700	0.701	0.703	0.705	0.707
45	0.708	0.705	0.702	0.700	0.698	0.697	0.697	0.697	0.697	0.698	0.700	0.701	0.703	0.704	0.707
50	0.709	0.705	0.702	0.700	0.698	0.697	0.697	0.697	0.697	0.698	0.699	0.701	0.703	0.704	0.706
55	0.710	0.706	0.702	0.700	0.698	0.697	0.697	0.697	0.697	0.698	0.699	0.701	0.702	0.704	0.706
60	0.710	0.706	0.703	0.700	0.699	0.698	0.697	0.697	0.697	0.698	0.699	0.701	0.702	0.704	0.706
65	0.711	0.707	0.703	0.701	0.699	0.698	0.697	0.697	0.697	0.698	0.699	0.701	0.702	0.704	0.706
70	0.712	0.707	0.704	0.701	0.699	0.698	0.697	0.697	0.698	0.698	0.699	0.701	0.702	0.704	0.706
75	0.712	0.708	0.704	0.701	0.699	0.698	0.697	0.697	0.698	0.698	0.699	0.701	0.702	0.704	0.706
80	0.713	0.708	0.704	0.702	0.700	0.698	0.698	0.697	0.698	0.698	0.699	0.701	0.702	0.704	0.706
85	0.714	0.709	0.705	0.702	0.700	0.698	0.698	0.697	0.698	0.698	0.699	0.701	0.702	0.704	0.706
90	0.715	0.709	0.705	0.702	0.700	0.699	0.698	0.698	0.698	0.698	0.699	0.701	0.702	0.704	0.706
95	0.716	0.710	0.706	0.703	0.700	0.699	0.698	0.698	0.698	0.699	0.699	0.701	0.702	0.704	0.706
100	0.716	0.711	0.706	0.703	0.701	0.699	0.698	0.698	0.698	0.699	0.700	0.701	0.702	0.704	0.706
105	0.717	0.711	0.707	0.703	0.701	0.699	0.698	0.698	0.698	0.699	0.700	0.701	0.702	0.704	0.706
110	0.718	0.712	0.707	0.704	0.701	0.700	0.699	0.698	0.698	0.699	0.700	0.701	0.702	0.704	0.706
115	0.719	0.712	0.708	0.704	0.702	0.700	0.699	0.698	0.698	0.699	0.700	0.701	0.702	0.704	0.706
120	0.719	0.713	0.708	0.705	0.702	0.700	0.699	0.698	0.698	0.699	0.700	0.701	0.702	0.704	0.706
125	0.720	0.714	0.709	0.705	0.702	0.700	0.699	0.699	0.699	0.699	0.700	0.701	0.703	0.704	0.706
130	0.721	0.714	0.709	0.705	0.702	0.701	0.699	0.699	0.699	0.699	0.700	0.701	0.703	0.704	0.706
135	0.722	0.715	0.710	0.706	0.703	0.701	0.700	0.699	0.699	0.699	0.700	0.701	0.703	0.704	0.706
140	0.723	0.715	0.710	0.706	0.703	0.701	0.700	0.699	0.699	0.699	0.700	0.701	0.703	0.704	0.706
145	0.723	0.716	0.711	0.706	0.703	0.701	0.700	0.699	0.699	0.700	0.700	0.701	0.703	0.704	0.706
150	0.724	0.717	0.711	0.707	0.704	0.702	0.700	0.699	0.699	0.700	0.700	0.701	0.703	0.704	0.706
155	0.725	0.717	0.712	0.707	0.704	0.702	0.700	0.700	0.699	0.700	0.700	0.702	0.703	0.704	0.706
160	0.725	0.718	0.712	0.708	0.704	0.702	0.701	0.700	0.700	0.700	0.701	0.702	0.703	0.705	0.706
165	0.726	0.718	0.712	0.708	0.705	0.702	0.701	0.700	0.700	0.700	0.701	0.702	0.703	0.705	0.706
170	0.727	0.719	0.713	0.708	0.705	0.703	0.701	0.700	0.700	0.700	0.701	0.702	0.703	0.705	0.706
175	0.728	0.720	0.713	0.709	0.705	0.703	0.701	0.700	0.700	0.700	0.701	0.702	0.703	0.705	0.706
180	0.728	0.720	0.714	0.709	0.706	0.703	0.702	0.701	0.700	0.700	0.701	0.702	0.703	0.705	0.707
185	0.729	0.721	0.714	0.710	0.706	0.703	0.702	0.701	0.700	0.701	0.701	0.702	0.703	0.705	0.707
190	0.730	0.721	0.715	0.710	0.706	0.704	0.702	0.701	0.701	0.701	0.701	0.702	0.703	0.705	0.707
195	0.730	0.722	0.715	0.710	0.707	0.704	0.702	0.701	0.701	0.701	0.701	0.702	0.704	0.705	0.707
200	0.731	0.722	0.716	0.711	0.707	0.704	0.702	0.701	0.701	0.701	0.701	0.702	0.704	0.705	0.707
205	0.732	0.723	0.716	0.711	0.707	0.704	0.703	0.702	0.701	0.701	0.702	0.702	0.704	0.705	0.707
210	0.732	0.723	0.717	0.711	0.708	0.705	0.703	0.702	0.701	0.701	0.702	0.703	0.704	0.705	0.707
215	0.733	0.724	0.717	0.712	0.708	0.705	0.703	0.702	0.701	0.701	0.702	0.703	0.704	0.705	0.707
220	0.734	0.724	0.717	0.712	0.708	0.705	0.703	0.702	0.702	0.702	0.702	0.703	0.704	0.705	0.707
225	0.734	0.725	0.718	0.712	0.708	0.706	0.704	0.702	0.702	0.702	0.702	0.703	0.704	0.706	0.707
230	0.735	0.725	0.718	0.713	0.709	0.706	0.704	0.702	0.702	0.702	0.702	0.703	0.704	0.706	0.707
235	0.735	0.726	0.719	0.713	0.709	0.706	0.704	0.703	0.702	0.702	0.702	0.703	0.704	0.706	0.707
240	0.736	0.726	0.719	0.714	0.709	0.706	0.704	0.703	0.702	0.702	0.702	0.703	0.704	0.706	0.707

Figures 3 and 4 show typical graphs of the effect of temperature

FIGURE 3. - Isobaric Variation of Prandtl Numbers With Temperature.

FIGURE 4. - Isothermal Variation of Prandtl Numbers With Pressure.

and pressure upon the Prandtl numbers of nitrogen.

DISCUSSION

Deviations between computed thermal conductivity values and the more reliable measurements of this property are small, and the correlation equations presented should be suitable for the prediction of thermal conductivity coefficients in areas not covered by experiments.

It is estimated that the accuracy of the tabulated thermal conductivity values corresponds to the accuracy of the initial data, except for data in the near-critical region of nitrogen.

The design of an apparatus for the determination of thermal conductivity values requires a knowledge of the laws of heat transfer. The Rayleigh criterion used by investigators (9, 14, 20, 24) in evaluating the design of their thermal-conductivity cells describes a heat transfer process where buoyancy is the only driving force. The Reynolds number in equation 3 is superfluous in the case of free convection, fluid motion is a direct consequence of buoyant and viscous forces only, and equality of Grashof numbers establishes dynamic similarity in homologous systems. For homologous systems, surfaces enclosing fluid masses must be geometrically similar, and the physical properties of fluids at corresponding points in

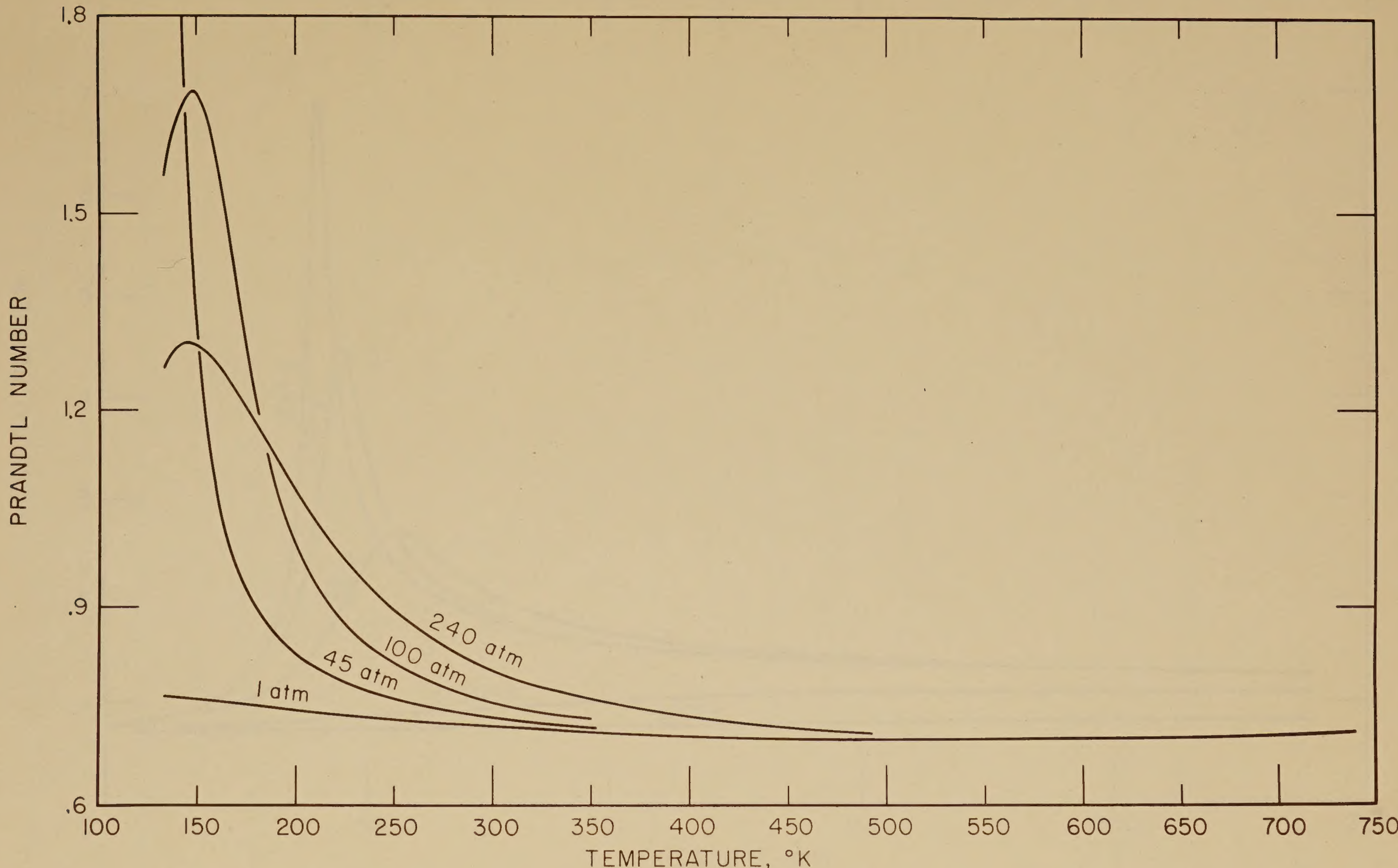

FIGURE 3.— Isobaric Variation of Prandtl Numbers With Temperature.

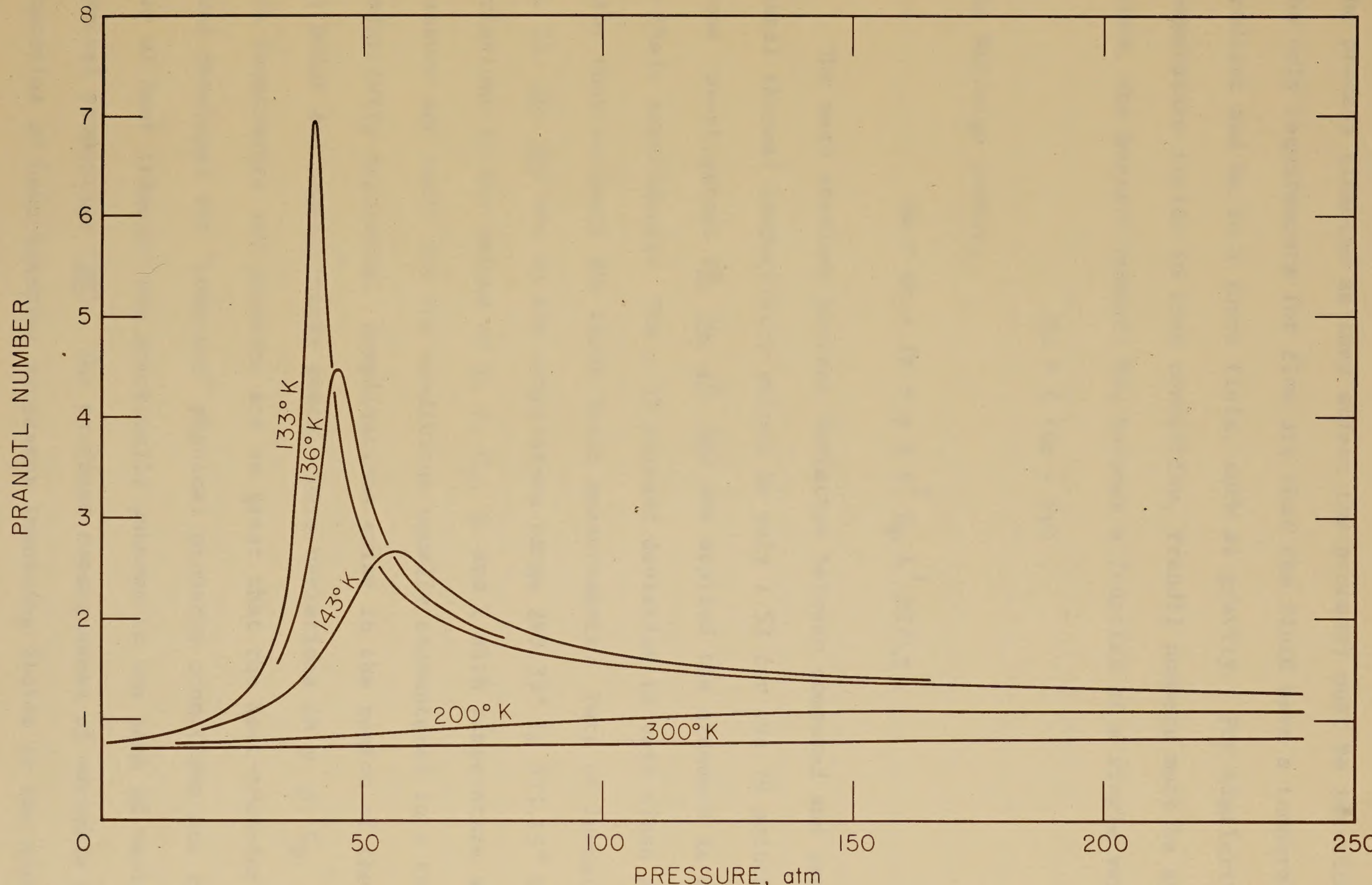

FIGURE 4.—Isothermal Variation of Prandtl Numbers With Pressure.

the process (insofar as they affect the process) must be identical. The only requirements for flow are that the fluid have a temperature gradient and be in a force field, such as gravity. For similarity of temperature fields in free convection, Prandtl numbers must be equal. Hence, the Nusselt number, Nu, becomes a function of a single variable,

$$Nu = f\ (Gr \cdot Pr)\ , \tag{14}$$

the Rayleigh number,

$$Ra = Gr \cdot Pr = \varphi\, g\, \rho^2\, C_p\, L^3\, \Delta T/\lambda \eta\ .$$

The mean absolute percent deviation between computed and experimental thermal conductivity values is only 1.53 for the 79 points of those investigators (9, 14, 20, 24) who applied the standard Ra $\leq$ 1,000 to their experiments. The 1.53 percent deviation is very close to the error they estimate for their basic measurements. Data of investigators (9, 14, 20, 24) are in the temperature range 295.35° to 973.15° K where variations in the values of φ, ρ, C_p, η, and λ with temperature and pressure are small for the conditions usually encountered in a thermal conductivity apparatus. Complications arise in the region of the critical point and supercritical state. Here variations in φ, ρ, C_p, η, and λ with temperature and pressure are so great that the heat-transfer equations developed for "constant" physical property conditions are invalid. Laws of heat transfer are practically unknown in the case of variable physical properties (28). The profound consequences of variable physical properties on heat-transfer processes involving fluids in the supercritical state are discussed by Petukhova (28).

The isobaric specific heat, C_p, and the coefficient of cubical expansion, φ, both become infinite at the crtical point. The behavior of real fluids at or near the critical point is not established beyond doubt; but, in general, it is assumed that viscosity, η, and thermal conductivity, λ, show monotonic variation in this region, as can be seen in figure 2 for the thermal conductivity of nitrogen. Both the Rayleigh and Prandtl numbers become infinite at the critical point and show irregular behavior at near-critical conditions. Variations of the Prandtl number with temperature and pressure are shown in figures 3 and 4.

Considering the extreme experimental difficulties encountered in the procurement of basic data in the near-critical region, the experimental results of Borovik (3), Golubev and Kalsina (11), Uhlir (35), and Ziebland and Burton (42), appear to be credible, although mutual agreement of thermal conductivity measurements is not very good.

Considering the experimental data used as a basis for the correlation equations, we estimate that uncertainties in the computed thermal conductivity values are ±5 percent for both dilute and compressed nitrogen. However, it is difficult to assess the uncertainties in the computed values at temperatures below 145° K for pressures between 20 and 70 atmospheres because the reliability of measurements in this area may be obscured by free-convective heat transfer. In general, the asymmetry of thermal conductivity measurements with respect to the regression equation in this region is for the computed thermal conductivity values to be underestimated. However, the relative skewness of the distribution of points about the

regression line is small, and large negative as well as large positive deviations are prominent. Therefore, the uncertainty in computed thermal conductivity values may rise to ±10 percent as near-critical conditions are approached.

Uncertainties of ±15 percent, in general, and ±30 percent, in the near-critical region, for the Prandtl numbers were computed from the estimated uncertainties in C_p, η, and λ by using the laws for the propagation of errors in arithmetic operations.

The thermal conductivities and Prandtl numbers of nitrogen computed in this work can be combined with the thermodynamic and transport properties of nitrogen computed in other programs (39-41) of the Bureau of Mines to form the working basis for engineering efforts to improve the design and efficiency of nitrogen refrigeration cycles used in helium technology.

regression line is small, and large negative as well as large positive deviations are prominent. Therefore, the uncertainty in computed thermal conductivity values may rise to ±10 percent as near-critical conditions are approached.

Uncertainties of ±15 percent, in general, and ±30 percent, in the near-critical region, for the Prandtl numbers were computed from the estimated uncertainties in C_p, η, and λ by using the laws for the propagation of errors in arithmetic operations.

The thermal conductivities and Prandtl numbers of nitrogen computed in this work can be combined with the thermodynamic and transport properties of nitrogen computed in other programs (39-41) of the Bureau of Mines to form the working basis for engineering efforts to improve the design and efficiency of nitrogen refrigeration cycles used in helium technology.

REFERENCES[5/]

1. Baker, Charles E., and Richard S. Brokaw. Thermal Conductivities of Gaseous H_2O, D_2O, and the Equimolar H_2O-D_2O Mixture. J. Chem. Phys., v. 40, No. 6, Mar. 15, 1964, pp. 1523-1528.

2. _____. Thermal Conductivities of Ordinary and Isotopically Substituted Polar Gases and Their Equimolar Mixtures. J. Chem. Phys., v. 43, No. 10, Nov. 15, 1965, pp. 3519-3528.

3. Borovik, E. Thermal Conductivity of Nitrogen. J. Phys. (U.S.S.R.), v. 11, No. 2, 1947, pp. 149-155.

4. Borovik, E., A. Matveev, and E. Panina. (Heat Conductivity of Liquid Nitrogen, Carbon Monoxide, Methane, and Ethylene.) Zhur. Tekhn. Fiziki (J. Tech. Phys.), v. 10, No. 12, 1940, pp. 988-998.

5. Chapman, S., and T. C. Cowling. The Mathematical Theory of Non-Uniform Gases. Cambridge Univ. Press, New York, 2d ed., 1952, 431 pp.

6. Cheung, Henry, LeRoy A. Bromley, and C. R. Wilke. Thermal Conductivity of Gas Mixtures. AIChE J., v. 8, No. 2, May 1962, pp. 221-228.

7. Childs, G. E., and H. J. M. Hanley. The Viscosity and Thermal Conductivity Coefficients of Dilute Nitrogen and Oxygen. NBS Tech. Note 350, Oct. 31, 1966, 27 pp.

8. Geier, H., and K. Schäfer. Wärmeleitfähigkeit von reinen Gasen und Gasgemischen zwischen 0° und 1200° C (Heat Conductivity of Pure Gases and Gas Mixtures at 0° - 1200° C). Allgem. Wärmetech., v. 10, No. 4, 1961, pp. 70-75.

9. Gilmore, Thomas F., and E. W. Comings. Thermal Conductivity of Binary Mixtures of Carbon Dioxide, Nitrogen, and Ethane at High Pressures: Comparison With Correlation and Theory. AIChE J., v. 12, No. 6, November 1966, pp. 1172-1178.

10. Golubev, I. F. (Viscosity of Gases and Gas Mixtures.) Moskva, Gosudarstvennoe Izdatel'stvo Fiziko-Matematicheckoi Literatury (Government Publishing House, Physico-Mathematical Literature, Moscow), 1959, 375 pp.

5/ Titles enclosed in parentheses are translations from the language in which the item was originally published.

11. Golubev, I. F., and M. V. Kalsina. (Thermal Conductivity of Nitrogen and Hydrogen at Temperatures From 20 to -195° C and Pressures From 1 to 500 atm.) Gaz. Prom., v. 9, No. 8, 1964, pp. 41-43.

12. Grout, Jarrell C. A General Computer Program for Solving Nonlinear Regression Problems. BuMines Inf. Circ. 8423, 1969, 35 pp.

13. Hirschfelder, Joseph O., Charles F. Curtiss, and R. Byron Bird. Molecular Theory of Gases and Liquids. John Wiley & Sons, Inc., New York, 1964, 1249 pp.

14. Johannin, P. Conductibilité Thermique de L'Azote Entre 75° et 700° C et Jusqua'a 1000 a 1600 Atmosphères (Thermal Conductivity of Nitrogen Between 75° and 700° C and to 1000 to 1600 Atmospheres). J. recherches centre nat. recherche sci., Lab. Bellevue (Paris), No. 43, June 1953, pp. 116-155.

15. Keyes, F. G. The Heat Conductivity, Viscosity, Specific Heat and Prandtl Numbers for Thirteen Gases. Tech. Rept. No. 37, Project Squid, Office Naval Res., Apr. 1, 1952, 33 pp.

16. _____. Measurements of the Heat Conductivity of Nitrogen-Carbon Dioxide Mixtures. Trans. ASME, v. 73, No. 5, July 1951, pp. 597-603.

17. _____. Thermal Conductivity of Gases. Trans. ASME, v. 77, No. 8, November 1955, pp. 1395-1396.

18. Keyes, F. G., and D. J. Sandell, Jr. New Measurements of the Heat Conductivity of Steam and Nitrogen. Trans. ASME, v. 72, No. 6, August 1950, pp. 767-778.

19. Keyes, F. G., and R. G. Vines. The Thermal Conductivity of Nitrogen and Argon. Trans. ASME, J. Heat Transfer, ser. C, v. 87, No. 2, May 1965, pp. 177-183.

20. Lenoir, J. M., and E. W. Comings. Thermal Conductivity of Gases. Measurement at High Pressure. Chem. Eng. Prog., v. 47, No. 5, May 1951, pp. 223-231.

21. Lenoir, J. M., W. A. Junk, and E. W. Comings. Measurement and Correlation of Thermal Conductivities of Gases at High Pressure. Chem. Eng. Prog., v. 49, No. 10, October 1953, pp. 539-542.

22. Mason, E. A., and L. Monchick. Heat Conductivity of Polyatomic and Polar Gases. J. Chem. Phys., v. 36, No. 6, Mar. 15, 1962, pp. 1622-1639.

11. Golubev, I. F., and M. V. Kalsina. (Thermal Conductivity of Nitrogen and Hydrogen at Temperatures From 20 to -195° C and Pressures From 1 to 500 atm.) Gaz. Prom., v. 9, No. 8, 1964, pp. 41-43.

12. Grout, Jarrell C. A General Computer Program for Solving Nonlinear Regression Problems. BuMines Inf. Circ. 8423, 1969, 35 pp.

13. Hirschfelder, Joseph O., Charles F. Curtiss, and R. Byron Bird. Molecular Theory of Gases and Liquids. John Wiley & Sons, Inc., New York, 1964, 1249 pp.

14. Johannin, P. Conductibilité Thermique de L'Azote Entre 75° et 700° C et Jusqu'à 1000 a 1600 Atmosphères (Thermal Conductivity of Nitrogen Between 75° and 700° C and to 1000 to 1600 Atmospheres). J. recherches centre nat. recherche sci., Lab. Bellevue (Paris), No. 43, June 1953, pp. 116-135.

15. Keyes, F. G. The Heat Conductivity, Viscosity, Specific Heat and Prandtl Numbers for Thirteen Gases. Tech. Rept. No. 37, Project Squid, Office Naval Res., Apr. 1, 1952, 33 pp.

16. ______. Measurements of the Heat Conductivity of Nitrogen-Carbon Dioxide Mixtures. Trans. ASME, v. 73, No. 5, July 1951, pp. 597-603.

17. ______. Thermal Conductivity of Gases. Trans. ASME, v. 77, No. 8, November 1955, pp. 1395-1396.

18. Keyes, F. G., and D. J. Sandell, Jr. New Measurements of the Heat Conductivity of Steam and Nitrogen. Trans. ASME, v. 72, No. 6, August 1950, pp. 767-778.

19. Keyes, F. G., and R. G. Vines. The Thermal Conductivity of Nitrogen and Argon. Trans. ASME, J. Heat Transfer, ser. C, v. 87, No. 2, May 1965, pp. 177-183.

20. Lenoir, J. M., and E. W. Comings. Thermal Conductivity of Gases. Measurement at High Pressure. Chem. Eng. Prog., v. 47, No. 5, May 1951, pp. 223-231.

21. Lenoir, J. M., W. A. Junk, and E. W. Comings. Measurement and Correlation of Thermal Conductivities of Gases at High Pressure. Chem. Eng. Prog., v. 49, No. 10, October 1953, pp. 539-542.

22. Mason, E. A., and L. Monchick. Heat Conductivity of Polyatomic and Polar Gases. J. Chem. Phys., v. 36, No. 6, Mar. 15, 1962, pp. 1622-1639.

23. Michels, A., and A. Botzen. The Thermal Conductivity of Nitrogen at Pressures up to 2500 Atmospheres. Physica, v. 19, July 1953, pp. 585-598.

24. Misic, Dragoslav, and George Thodos. Thermal Conductivity Measurements for Nitrogen in the Dense Gaseous State. AIChE J., v. 11, No. 4, July 1965, pp. 650-656.

25. Nuttall, R. L., and D. C. Ginnings. Thermal Conductivity of Nitrogen From 50° to 500° C and 1 to 100 Atmospheres. J. Res. NBS, v. 58, No. 5, Res. Paper 2760, May 1957, pp. 271-278.

26. Pereira, A. N. G., and C. J. G. Raw. Heat Conductivities of Polyatmoic Gases and Their Binary Mixtures. Phys. Fluids, v. 6, No. 8, August 1963, pp. 1091-1096.

27. Peterson, J. N., T. F. Hahn, and E. W. Comings. Thermal Conductivity of Mixtures of Argon-Helium and Argon-Nitrogen. AIChE Symp. on Advances in High Pressure Technology--Part III, 64th National Meeting, New Orleans, La., Mar. 16-20, 1969. The American Institute of Chemical Engineers, New York, Preprint 43 A, 1969, 19 pp.

28. Petukhov, B. S. (Heat Transfer in a Single-Phase Medium Under Supercritical Conditions.) Academy of Science of the U.S.S.R., Transl. from Teplofizika Vysokikh Temperatur, v. 6, No. 40, July-August 1968, pp. 732-745. English translation in High Temperature, v. 6, No. 4, July-August 1968, pp. 696-709.

29. Powell, R. W., C. Y. Ho, and P. E. Liley. Thermal Conductivity of Selected Materials. National Standard Reference Data Series-National Bureau of Standards--8, NSRDS-NBS 8, Nov. 25, 1966, 168 pp.

30. Reid, Robert C., and Thomas K. Sherwood. The Properties of Gases and Liquids. McGraw-Hill Book Co., Inc., New York, 2d ed., 1966, 646 pp.

31. Rothman, Albert J. Thermal Conductivity of Gases at High Temperatures (Thesis). Radiation Lab., Univ. California, Berkeley, U.S. AEC, UCRL-2339, January 1954, 115 pp.

32. Rothman, Albert J., and LeRoy A. Bromley. High Temperature Thermal Conductivity of Gases. Measurements on Nitrogen, Carbon Dioxide, Argon, and Nitrogen-Carbon Dioxide Mixtures at Temperatures up to 775° C. Ind. and Eng. Chem., v. 47, No. 5, May 1955, pp. 899-906.

33. Stoliarov, E. A., V. V. Ipat'ev, and V. P. Teodorovich. (Transfer Phenomena in Compressed Gases. I. Determination of the Heat Conductivity Coefficients of Compressed Gases (H_2, N_2, Air, CH_4, and CO_2).) Zhur. Fiz. Khim., v. 24, No. 2, 1950, pp. 166-176.

34. Tsederberg, N. V. Thermal Conductivity of Gases and Liquids. The M.I.T. Press, Cambridge, Mass., 1965, 246 pp.

35. Uhlir, Arthur, Jr. Thermal Conductivity of Fluid Argon and Nitrogen. J. Chem. Phys., v. 20, No. 3, March 1952, pp. 463-472.

36. Vargaftik, N. B., and N. Kh. Zimina. (Thermal Conductivity of Nitrogen at High Temperatures.) Moscow Aviation Inst., Transl. from Teplofizika Vysokikh Temperatur, v. 2, No. 6, November-December 1964, pp. 869-878. English translation in High Temperature, v. 2, No. 6, November-December 1964, pp. 782-790.

37. Vines, Robert G. Measurement of the Thermal Conductivities of Gases at High Temperatures. Trans. ASME, J. Heat Transfer, ser. C, v. 82, No. 1, February 1960, pp. 48-52.

38. Westenberg, A. A., and N. deHaas. Gas Thermal-Conductivity Studies at High Temperature. Line-Source Technique and Results in N_2, CO_2, and N_2-CO_2 Mixtures. Phys. Fluids, v. 5, No. 3, March 1962, pp. 266-273.

39. Wood, Robert E. Thermodynamic Properties of Helium, Nitrogen, and Helium-Nitrogen Mixtures From 240° to 950° R for Pressures Between 14.696 and 3,000 PSIA. BuMines Rept. of Inv. 7190, October 1968, 361 pp.

40. Wood, Robert E., and W. J. Boone, Jr. Viscosity of the Helium-Nitrogen System From 133° to 740° K for Pressures Between 1 and 240 Atmospheres. BuMines Rept. of Inv. 7405, July 1970, 130 pp.

41. Wood, Robert E., W. J. Boone, Jr., J. D. Marshall, and F. W. Baer. Equation of State for Helium-Nitrogen Mixtures From 133.15° to 748.15° K With Pressures to 300 Atmospheres. BuMines Rept. of Inv. 6896, 1967, 178 pp.

42. Ziebland, H., and J. T. A. Burton. The Thermal Conductivity of Nitrogen and Argon in the Liquid and Gaseous States. British J. Appl. Phys., v. 9, No. 2, February 1958, pp. 52-59.